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LEVEL II

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EXPERIMENTAL VERIFICATION AND REVISION OF THE VENTING RATE MODEL OF THE HAZARD ASSESSMENT COMPUTER SYSTEM AND THE VULNERABILITY MODEL

FINAL REPORT

NOVEMBER 1980

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16. Abstract

A model developed previously as part of the Hazard Assessment Computer System to predict the discharge rate of a chemical cargo from a punctured ship tank has been revised and verified. The computerized model can now treat: (1) a puncture above, below, or intersecting the waterline; (2) vacuum relief valve actuations; (3) simultaneous liquid and gas discharge; (4) volatile or nonvolatile cargo; and (5) air or water ingestion into the tank, to permit additional cargo to be discharged. The model is based on an analysis of such thermodynamic and fluid flow phenomena as two-phase and choked flow and realistic evaporation rates within the tank. The Chemical Properties File was examined for its applicability to the revised model, and some desirable improvements were indicated. Experimental verification of the model consisted of a series of extensively instrumented tests of small tanks to investigate: (1) discharge coefficients of irregularly shaped punctures; (2) air and water ingestion; and (3) discharge of volatile and boiling liquids. The good comparison of the model to the tests adequately verified the model.

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METRIC CONVERSION FACTORS

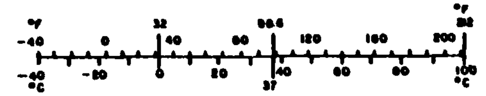
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



SUMMARY

This final report covers all four tasks of a project to revise and verify experimentally the Venting Rate Model of the Hazards Assessment Computer System. The report documents (1) all experimental procedures and representative test data, and (2) the analysis, development, and verification of the final form of the model.

<u>Background</u>. An analytical/computer model had been previously developed for the U. S. Coast Guard for use in predicting the discharge of a liquid or gas cargo from a punctured ship tank. A later independent review found that the model contained a number of errors and inappropriate assumptions. The review generally concluded that the model should be revised and verified experimentally. The present program was therefore sponsored by the Coast Guard to accomplish the recommended revision and verification.

<u>Tasks 1 and 2 - Review and Reformulation of the Model</u>. During the first two tasks of this program, the Venting Rate Model and other relevant literature were reviewed, and the model was then completely reformulated. The new model is applicable to nearly every practical combination of puncture location , cargo properties, intermittent outflows, and relief valve actuations. In summary, the new model incorporates:

- puncture locations above or below the waterline;
- vacuum relief valve actuations;
- possibility of air in the cargo vapor space;
- changes of phase during the discharge of a volatile cargo;
- choked flow discharges of gases and volatile liquids;
- simultaneous liquid and gas discharges;
- air or water ingestion through the puncture; and
- effects of realistic evaporation rates of volatile liquids within the tank.

Temperature stratification of a volatile liquid, one of the phenomena suggested by the review as perhaps being important enough to be included in the model, was investigated experimentally and found to be negligible. Thus, stratification is not included in the new model.

The model has been programmed for computerized solution. Program listings and flow charts are included in this report.

The Chemical Properties File was also reviewed for its applicability to the revised Venting Rate Model. Data correlations for cargo properties of nonvolatile cargos were found to be satisfactory. However, several serious limitations were discovered for volatile cargos; namely: (1) the compressibility and the specific heat of the saturated vapor should be included; (2) the vapor pressure vs temperature correlations are moderately inaccurate; and (3) a correlation giving the latent heat of vaporation as a function of temperature should be included. More accurate and complete correlations for six representative cargos were also developed.

<u>Task 3 - Experimental Program</u>. The third task of the program was an extensive series of model-scale experiments. The overall objectives of these tests were:

- obtain data to evaluate the assumptions used in developing the analytical models;
- gain insight into air and water ingestion; and
- acquire discharge rate data for a variety of test conditions to validate the overall Venting Rate Model.

The <u>first test series</u> determined the discharge coefficients for a variety of realistically shaped punctures over a range of Reynolds numbers. These tests showed that a discharge coefficient of 0.65 is adequate for nearly all puncture shapes; the exceptions are vertical or horizontal slot-like punctures with ragged edges pointing outwards, for which the recommended discharge coefficient is 0.825.

The <u>second test series</u> was designed to study the ingestion of air or water (for submerged punctures) through the puncture. It was found that air or water ingestion can result in the discharge of more cargo than would be predicted by the previous Venting Rate Model when the ambient pressure exceeds the tank pressure at the puncture location. The tests were used to obtain physical insight about air and water ingestion, from which relatively simple but realistic analytical models were developed.

The <u>third test series</u> studied the discharge of volatile cargos. The specific objectives of these tests were: (1) evaluate the importance of liquid stratification; (2) gain insight and obtain quantitative data about evaporation within the tank; (3) evaluate the effects of phase changes of the discharge (two-phase outflow); and (4) obtain discharge data (e.g., time durations, temperatures, tank pressure, mass rate of outflow) which could be used for the overall verification of the revised analytical/computer model.

As indicated above, these tests showed that liquid stratification was negligible. The effects of evaporation rate, however, were found to be significant when the vacuum relief valve is jammed shut or when the cargo is transported at super-atmospheric pressure. Evaporation within the tank tends to keep the partial pressure of the vapor in the tank at some value intermediate between the saturation pressure of the liquid and the pressure that corresponds to the expansion of a gas whose mass does not increase as the vapor space volume increases during the discharge. Since the tank pressure is an important factor in predicting the discharge rate, a new model of evaporation rates appropriate for closed tanks was developed. The tests also showed that the discharge rate of liquids was limited by changes of phase to smaller values than would be predicted by the single-phase flow relations used in the previous Venting Rate Model. Two-phase flow models were therefore developed.

Task 4 - Model Verification. In this task, the Venting Rate Model was compared to the test data and revised as indicated by the comparisons. This was, in fact, a continuing process during the entire project.

Each submodel of the overall model was first compared to representative test data relevant to that model and then corrected when necessary. In addition, the tests were used to determine the best values for any empirical constants appearing in the model. It should be noted that no submodel required more than one such empirical constant and that the values of the constants were all physically reasonable.

The entire model was then compared to tests for many different kinds of cargo discharge:

- nonvolatile liquids, with and without operable vacuum relief valves;
- air ingestion during the discharge of volatile and nonvolatile liquids;
- water ingestion during the discharge of nonvolatile liquids heavier and lighter than water; and
- volatile liquids transported at slightly super-atmospheric pressures.

The comparisons of the model to these tests were very good.

It is concluded that the revised model is now satisfactory for use in the Hazards Assessment Computer System.

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LIST OF ILLUSTRATIONS (Cont'd)

PRINCIPAL SYMBOLS

<u>English Symbols</u>

A_p	area of puncture
A_{Lo}, A_{Vo}	puncture areas occupied by liquid and gas discharges
A_{in}, A_{out}	puncture areas occupied by air ingestion inflow and cargo liquid outflow
A_T	tank cross-sectional area
C_D	discharge coefficient
C_{PA}	specific heat of air (constant pressure)
C_{PL}	specific heat of cargo liquid (constant pressure)
$\bar{C}_{PV}$	specific heat of cargo vapor (along saturation line)
g	acceleration of gravity
h_L	specific enthalpy of liquid
K	empirical constant in water ingestion models
M_A, M_L, M_V	masses of air, liquid, and vapor in tank
P_V	partial pressure of vapor in tank
P_T	tank vapor-space pressure
P_∞	ambient pressure (includes hydrostatic head of water when the puncture is submerged)
R	gas constant of cargo vapor
R_m	gas constant of air/vapor mixture
t	time
T	cargo temperature
T_{air}	air temperature
v_L, v_V	specific volume of liquid and vapor
V_T	tank volume

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PRINCIPAL SYMBOLS (Cont'd)

W_A	mass flow rate of air into tank
W_e	mass rate of evaporation at liquid/vapor interface
W_{Ao}, W_{Lo}, W_{Vo}	mass flow rates of air, liquid, and vapor discharges
W_w	mass flow rate of water into tank
x_c	quality of two-phase choked flow
Z	compressibility factor of vapor
Z_L	elevation of cargo liquid surface above tank bottom
Z_{Lh}, Z_{Gh}	elevation of liquid and gas discharge streams above tank bottom
Z_T	elevation of tank top above bottom
Z_W, Z_{WT}	elevation of outside water surface and water surface in tank

Greek Symbols

β	two-phase flow parameter, see eq. (II.7b)
γ_m	ratio of specific heats for vapor or vapor/air mixture
ΔP_{valve}	vacuum set-point opening of relief valve
λ	latent heat of evaporation
ρ_L, ρ_W	density of cargo liquid and water

Other Subscripts

c	related to choked flow
Eq.	related to equilibrium of outside pressure and tank pressure at puncture elevation
i	initial value
s	related to constant entropy process in which the pressure is reduced to ambient

I. INTRODUCTION

As part of the Hazards Assessment Computer System (HACS) of the Chemical Hazards Response Information System, a model was previously developed to predict the rate of liquid or gaseous cargo discharged to the environment by an accidental rupture of a ship tank [1]. An independent review of this model later revealed several errors in its basic equations and a lack of realism in some of its underlying assumptions [2]. The Coast Guard has sponsored the present program to correct these deficiencies and to validate the corrected model experimentally.

Errors in the basic equations and incorrect assumptions made in developing the previous model included:

- the thermodynamic energy balance used to predict tank pressure and temperature for volatile cargos was incorrect;
- incompressible flow equations were used to predict the venting of a volatile liquid, even though the liquid partially vaporizes during the venting;
- the discharge was assumed to cease when the pressure differential across the puncture was zero, even if the liquid cargo level were still above the puncture; that is, ingestion of air or water through the puncture was ignored although this would allow the remaining liquid cargo above the puncture to be discharged; and
- incorrect values were recommended for the discharge coefficients of the puncture.

Other stated or implied assumptions that may be unrealistic or inappropriate included:

- no provision was made for vacuum relief valves;
- all punctures were above the waterline;

- simultaneous venting of liquid and gas did not occur;
- air was not present in the vapor space;
- the specific heat of superheated vapor was used to compute enthalpy changes of saturated vapor;
- evaporation at the liquid-gas interface in the tank was computed by assuming the vapor remained saturated; and
- temperature stratification in the liquid resulting from evaporation was negligible.

The consequences of these errors and assumptions could not always be determined solely by examining the model or its predictions. For example, potential errors in the evaporation model could not be evaluated because a more realistic model was not available. Further, the overall accuracy of the venting rate model was unknown.

The present program was designed to correct these errors and to validate the models. It had the following scope.

1. Review the venting rate model and any other relevant literature, with the aim of uncovering errors, inconsistencies, and unrealistic assumptions.
2. Correct and reformulate the venting rate model and reprogram it for computerized solution.
3. Review the Chemical Properties File of HACS for applicability to the corrected venting rate model.
4. Conduct a sensitivity analysis of the computed results to the input variables.
5. Design and conduct a model-scale test program to obtain venting rate data for tank conditions and cargo conditions analogous to full scale.
6. Revise the venting rate model as indicated by the correlation of the test data and the model predictions.

These efforts were arranged into four tasks. Task 1 covered the first effort given above; Task 2 covered the next three; Task 3 covered the fifth effort; and Task 4 covered the last effort. To present a more readable narrative, this final report is not arranged strictly by tasks. The complete analytical model development is presented first (Tasks 1, 2, and 4). Then the test program (Task 3) is described. Comparisons of the tests and the model predictions are given next, followed by the conclusions and appendices, which incorporate the sensitivity analysis and the review of the Chemical Properties File.

II. TASK II. REFORMULATION OF MODEL

The venting rate model was reformulated in detail in the Interim Report [3]. A summary of that development is presented in this section, with a complete derivation presented in Appendix A. More complete details of the air and water ingestion submodels and the evaporation rate model will be given, however, since they were not fully developed at the time the Interim Report was issued.

II.1 Reformulation of Tank Energy Balance

The total mass of cargo discharged can sometimes be easily estimated (for example, the quantity of liquid above the puncture). But the venting rates and the time required for the venting can only be determined by coupling energy and mass balances which describe the time-varying pressure and temperature of the cargo within the tank cargo to models of the discharge rate through the puncture. As in AMSHAH [1], two limiting conditions are assumed in formulating the energy balances:

(1) all processes occurring in the tank are adiabatic, or

(2) all processes occurring in the tank are isothermal.

These assumptions eliminate the need to consider energy transfers with the outside and thus greatly simplify the models. Furthermore, predictions made using these assumptions will bound the actual tank conditions. In addition, isothermal and adiabatic conditions are practically identical for a nonvolatile cargo, since the temperature changes little during the venting, and so for this case the assumption of which process actually occurs is not important.

The critical review [2] of AMSHAH's model concluded that temperature stratification as a result of heat and mass transfer between the liquid and vapor phases of the cargo within the tank might need to be accounted for in the energy balances. Experimental results to be described later show, however, that

the temperature stratification is small and has only a negligible effect on the tank energy balance, even for very rapid venting of volatile cargos. In agreement with the original models, then, a "well stirred reactor" approach is assumed.

Considering the control volume shown in Figure II.1 and assuming for the moment that the processes within the tank are adiabatic, the correct form of the energy balance for the cargo in the tank is [3]:

$$(M_L C_{PL} + M_V \bar{C}_{PV} + M_A C_{PA}) \frac{dT}{dt} = \forall_T \left(\frac{dP_T}{dt}\right) + \lambda \left(\frac{dM_L}{dt} + W_{Lo}\right) + W_A C_{PA} (T_{air} - T) \qquad \text{(II.1)}$$

The negligible changes in gravitational potential energy and kinetic energy have been ignored in this equation [1,2,3]. The bar over $\bar{C}_{PV}$ is meant to emphasize that the enthalpy change of saturated vapor ($dh_V = \bar{C}_{PV} dT$) is the relevant quantity for the vapor, for which C_p of superheated vapor is a poor approximation. For isothermal processes, equation (II.1) reduces simply to T = constant = initial temperature.

The mass balances which must be used with equation (II.1) are:

$$\frac{dM_L}{dt} = -W_{Lo} - W_e \qquad \text{(II.2a)}$$

$$\frac{dM_V}{dt} = -W_{Vo} + W_e \qquad \text{(II.2b)}$$

$$\frac{dM_A}{dt} = -W_{Ao} + W_A \qquad \text{(II.2c)}$$

Since $\forall_T = v_L M_L + v_V M_V$, where the specific volume of the vapor is based on its partial pressure in the air/vapor mixture in the vapor space, and since $d\forall_T/dt = 0$, equations (II.2a) and (II.2b) can be combined to give a relation for the evaporation rate:

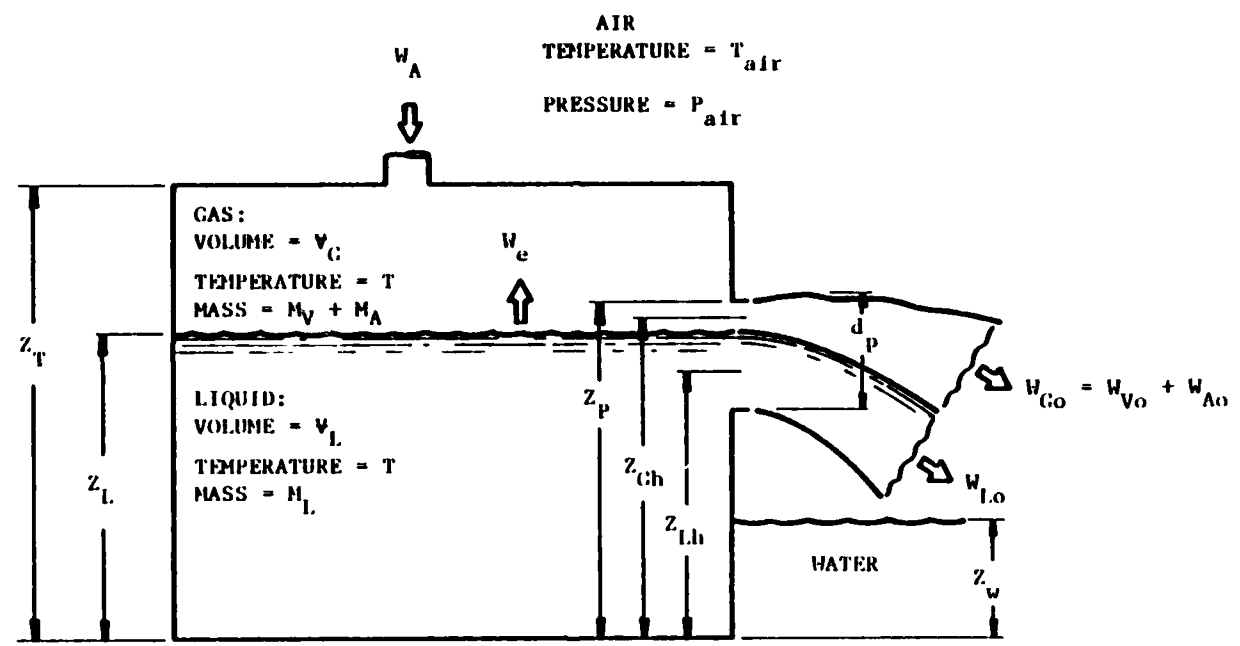


FIGURE II.1. NOMENCLATURE FOR TANK ENERGY BALANCE

$$W_e = \left[v_L W_{Lo} + v_V W_{Vo} - M_L \frac{dv_L}{dt} - M_V \frac{dv_V}{dt}\right] \Big/ (v_V - v_L) \quad \text{(II.3)}$$

Equations (II.1) - (II.3) constitute the reformulated tank energy and mass balances that are appropriate for volatile cargos.

For a nonvolatile cargo (vapor pressure at normal temperature is much smaller than atmospheric pressure), the previous mass and energy balances include many zero or near-zero terms, and a numerical solution using these equations would be unduly complicated. Only the mass balances (equations (II.2) with $W_e = 0$) and a relation that gives the change in the vapor space pressure when the vapor space volume changes are required. If the vacuum relief valve is jammed shut, the pressure relation follows from the adiabatic expansion relation:

$$P_T = P_{Ti} \left(\frac{V_T - M_{Li} v_{Li}}{V_T - M_L v_L} \right)^{\gamma_m} \quad \text{(II.4)}$$

where the subscript i indicates the initial conditions at the time the puncture is created. The exponent γ_m is equal to one for isothermal conditions, and equal to the ratio of specific heats of the vapor/air mixture in the vapor space for adiabatic conditions. If the relief valve is operable, equation (II.4) is still valid as long as the tank pressure remains above the set-point vacuum of the valve. Once the set-point is exceeded, the tank pressure relation is

$$P_T = P_{atm} - \Delta P_{valve} \quad \text{(II.5)}$$

since it is assumed that the valve always remains open thereafter.

II.2 Flow Rate Models

The next part of the venting rate model relates the discharge rates W_{Lo}, W_{Vo}, and W_{Ao} to the tank conditions.

When its vapor pressure is higher than atmospheric pressure, a venting liquid may partially vaporize and a venting vapor

may partially condense. These phenomena must be included in the flow models; the fact that they were not included in the models described in [1] limits their predictive accuracy, as will be discussed further in Section III.4. Although there are many correlations available to compute two-phase flow [4], they are all mathematically very complicated when a change of phase occurs within the flow stream. For this reason, a thermodynamic-equilibrium type of flow is assumed, but an empirically determined factor is applied to the effective density to increase the reliability of the predictions.

In general, a thermodynamic-equilibrium flow is given by

$$W_o = C_D A_o \rho_{out} \left[2 (h_{in} - h_{out}) + 2g (Z_{in} - Z_{out})\right]^{1/2} \quad \text{(II.6)}$$

where the subscript "in" refers to a location within the tank where the fluid velocity is small and "out" refers to the exit plane of the puncture. The discharge coefficient C_D is meant to account for irreversible flow and other nonideal effects. Equation (II.6) can be specialized to include volatile and nonvolatile liquids and gases. For a volatile liquid, the appropriate form is derived by assuming an isentropic process through the puncture; the result, as shown in Appendix A, is:

$$W_{Lo} = C_D A_{Lo} \rho_{Lo} \left\{2 \left[C_{PL} (T - T_s) - C_{PL} T_s \ln \frac{T}{T_s} + (P_T - P_V)/\rho_L + g (Z_L - Z_{Lh})\right]\right\}^{1/2} \quad \text{(II.7a)}$$

where ρ_{Lo} is the exit-plane density:

$$\rho_{Lo} = \left\{v_{Ls} + \left[\beta T_s (v_{Vs} - v_{Ls}) C_{PL} \ln \frac{T}{T_s}\right] \Big/ \lambda_s\right\}^{-1} \quad \text{(II.7b)}$$

Here, the subscript s indicates the saturated state at which the pressure is equal to the pressure P_∞ outside the tank (atmospheric, plus the static head of water if the puncture is submerged). The temperature T_s and the other properties (v_{Ls},

v_{Vs}, etc.) can be computed from the Chemical Properties File data. Average values over the temperature range T to T_s should be used for C_{PL} and ρ_L. The term $(P_T - P_V)$ in equation (II.7a) allows for the possibility that the vapor space pressure differs from the saturation pressure P_V corresponding to the liquid temperature.

The factor β in equation (II.7b) represents an empirical way to incorporate the experimental observation [25] that the actual fraction of the liquid vaporized is somewhat less than would be predicted by thermodynamic equilibrium relations. According to the tests described later, $\beta = 0.12$ gives a good correlation to the data. It is recognized that equations (II.7a) and (II.7b) are just an approximation to a complex two-phase flow [4], but the comparison of the model to the tests indicates that the approximation is satisfactory for this application.

The flow relation for a volatile vapor is similarly:

$$W_{Vo} = C_D A_{Vo} \rho_{Vo} \left\{ 2 \left[\bar{C}_{PV} (T - T_s) + ZRT_s \ln \frac{P_T}{P_\infty} - \bar{C}_{PV} T_s \ln \frac{T}{T_s} \right] \right\}^{1/2} \tag{II.8a}$$

where

$$\rho_{Vo} = \left\{ v_{Vs} - \beta \left[ZRT_s \ln \frac{P_T}{P_\infty} - T_s \bar{C}_{PV} \ln \frac{T}{T_s} \right] \frac{(v_{Vs} - v_{Ls})}{\lambda_s} \right\}^{-1} \tag{II.8b}$$

When a mixture of vapor and air is venting, the air tends to suppress the fairly small phase change effects of the vapor, so equation (II.6) in this case reduces to [5]:

$$W_{Vo} = \frac{C_D A_{Vo} P_T}{\sqrt{R_m T}} \left(\frac{v_A}{v_V + v_A} \right) \left\{ \frac{2\gamma_m}{\gamma_m - 1} \left[\left(\frac{P_T}{P_\infty} \right)^{\frac{2}{\gamma_m}} - \left(\frac{P_T}{P_\infty} \right)^{\frac{\gamma_m + 1}{\gamma_m}} \right] \right\}^{1/2} \tag{II.9a}$$

and

$$W_{Ao} = \left(\frac{v_V}{v_A}\right) W_{Vo} \qquad \text{(II.9b)}$$

The specific volumes of the vapor and air in the tank are based on their respective partial pressures.

For nonvolatile cargos, the flow equations for vapor or a vapor/air mixture are the same as (II.9a) and (II.9b). The flow equation for discharge of a nonvolatile liquid can be obtained by standard Bernoulli-type relations; it is:

$$W_{Lo} = C_D A_{Lo} \rho_L \left\{ 2[(P_T - P_\infty/\rho_L + g\ (Z_L - Z_{Lh})\ ] \right\}^{1/2} \qquad \text{(II.10)}$$

In all these models, as well as in the water and air ingestion models to be described subsequently, both vapor and liquid outflows can occur simultaneously. This is handled analytically by partitioning the total puncture area into a liquid outflow area A_{Lo} and a vapor outflow area A_{Go}.

II.3 Evaporation Rate Model

The discharge rates of liquid and gas depend on the vapor space pressure, P_T. Since evaporation of liquid into the vapor space during the discharge tends to keep P_T from decreasing as the vapor space volume increases, it is important to model the evaporation realistically.

Given the cargo temperature, the equilibrium pressure of the vapor (i.e., the liquid saturation pressure) can be computed from the Chemical Properties Files. The pressure and temperature fix the vapor density, so equation (II.3) can be used to determine the evaporation rate required to maintain the pressure at its equilibrium value. AMSHAH [1] used exactly this procedure. However, it is clear that to create the required evaporation rate there must be a driving force; the vapor space pressure must be less than the liquid saturation pressure [6,7]. The tests conducted during the present program confirmed this conclusion. Thus, v_V cannot be related only to the cargo

temperature, and equation (II.3) must be augmented by an evaporation rate model.

Evaporation rates from a liquid into the atmosphere are commonly related to the difference between the saturation pressure of the liquid and the actual partial pressure of the vapor in the air above the liquid [8]:

$$W_e = \alpha A_T (P_{V,sat} - P_V)/\sqrt{2\pi RT} \qquad \text{(II.11)}$$

where the coefficient α must be determined experimentally. For the present tests, where evaporation in a closed container was obtained, equation (II.11) could not be made to correlate the data very well; further, the best values of α appeared to vary widely from test to test, as a function of venting rates and chemical properties. By examining several kinds of correlations, it was found that a better data fit for these tests was given by:

$$W_e = W_{e,sat} - 1.9\ (W_{e,sat})^{5/4} \Big/ (A_T \rho_L \sqrt{RT})^{1/4} \qquad \text{(II.12)}$$

where $W_{e,sat}$ is the evaporation rate required to maintain the vapor partial pressure at its equilibrium value. The constant in equation (II.12) varied from about 1.6 to 2.2 from test to test, with the best average being 1.9. The rationale for equation (II.12) is given in Appendix A.

Although equation (II.12) implies that $P_{V,sat} - P_V$ is nonzero, it cannot be put in a form that reveals this dependency explicitly. However, the model does show that larger evaporation rates give larger differences between $W_{e,sat} - W_e$, and therefore larger pressure differences, $P_{V,sat} - P_V$.

In the computerized solution procedure, the evaporation rate model is used as follows. At any instant, $W_{e,sat}$ is calculated from equation (II.3) by assuming that the vapor is in equilibrium with the liquid. Equation (II.12) is then used to compute the corrected W_e. Using this value of W_e, equation

(II.3) is solved for v_V, and finally the actual vapor pressure is computed from the vapor equation of state: $P_V = ZRT/v_V$. Several iterations are required for convergence.

When the pressure at the puncture, e.g., $P_T + \rho_L g(Z_L - Z_{Lh})$, is substantially larger than P_∞, the changes in P_T during the venting have a relatively small effect on the discharge. Therefore, it is apparent that the effects of the evaporation rate on the discharge are likely to be small for large tanks.

II.4 Air and Water Ingestion Models

There are many cases in which air or water ingested into the tank through the puncture can cause additional cargo to be discharged. For example, when liquid is venting and the vacuum relief valve is jammed shut, a vacuum may eventually be created in the vapor space that is sufficient to lower the tank pressure at the puncture to the ambient pressure. Even though the net pressure differential across the puncture is now zero, the discharge will not cease if the liquid level is still above the puncture, although this was assumed to be the case in [1]. Instead, water or air (depending on whether the puncture is submerged) will be ingested to relieve the vacuum. For submerged punctures, water can be ingested even when the relief valve is operable.

II.4.1 Air Ingestion Model

Air can only be ingested when (1) liquid is being vented, (2) the puncture is not submerged, and (3) the static pressure, $P_T + \rho_L g\,(Z_L - Z_{Lh})$, at the puncture is nearly equal to atmospheric pressure. When all these conditions are met, typically when the relief valve is jammed shut, tests have shown that the outflow becomes intermittent. Air bubbles are ingested to relieve the vacuum in the vapor space, thereby halting the outflow temporarily; more liquid is then discharged, until $P_T + \rho_L g\,(Z_L - Z_{Lh})$ is again decreased to near atmospheric pressure; more air bubbles are ingested, and so on, until the liquid level falls below the top of the puncture; see Figure II.2a.

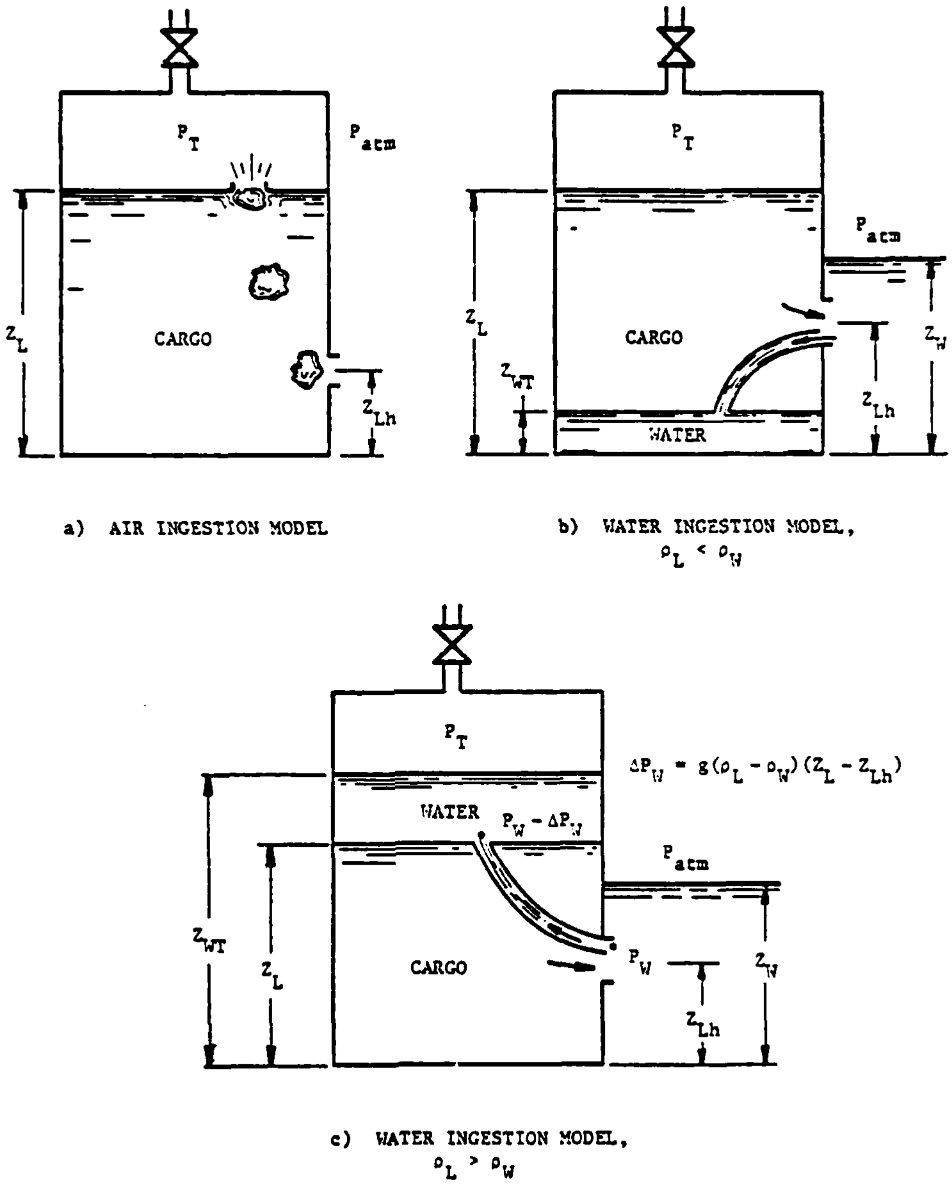


FIGURE II.2. AIR AND WATER INGESTION MODELS

The available literature on this kind of intermittent flow is sparse [9]. A relatively simple but plausible model has therefore been developed for the venting rate model. The model contains one empirical parameter (the bubble size factor) that is selected to give agreement with test results. In summary, the model is described as follows:

- Air ingestion begins when the combination of tank liquid level and vapor space pressure has decreased nearly to atmospheric pressure:

$$P_T - P_{atm} + g\rho_L (Z_L - Z_{Lh}) \leq 0.001\, P_{atm} \qquad \text{(II.13)}$$

- When (II.13) is satisfied, an air bubble is ingested whose volume is a specified multiple (the bubble size factor) of a sphere having a cross-sectional area equal to the puncture area.
- The vapor space pressure is increased by an amount ΔP_T corresponding to the addition of this bubble to the vapor space; for a volatile cargo, the ΔP_T calculation is accomplished by integrating equation (II.1) over an infinitesimal time step, Δt, with $W_A \Delta t$ set equal to the ingested bubble mass; for a nonvolatile cargo, the change in the specific volume of the vapor space gas mixture is computed, and ΔP_T is then calculated by ideal gas laws.
- Since the left hand side of equation (II.13) is now larger than the right hand side, additional liquid is discharged, in accordance with the appropriate energy balances and flow relations; the outflow continues until equation (II.13) is again satisfied.
- Another air bubble is ingested, and the process is repeated.

The right hand side of equation (II.13) is set equal to 0.001 P_{atm}, rather than to zero, to avoid numerical problems in the computerized model, by ensuring that the outflow has not ceased completely before the bubbles are ingested. Experiments have indicated that the value of the right hand side is between zero and about 0.002 P_{atm}, so equation (II.13) is reasonably accurate. As the vapor space volume increases, the increase in the pressure ΔP_T due to the ingestion of a single bubble becomes smaller, and the net ΔP driving the liquid outflow therefore becomes smaller; further, the hydrostatic head $Z_L - Z_{Lh}$ is smaller than it was originally. To prevent an excessive number of computational iterations, more than one bubble can be admitted when necessary. The criterion used in the computerized model is that the value of $P_T + \rho_L g (Z_L - Z_{Lh})$ after each bubble (or bubbles) has been admitted should be reasonably close to the value obtained after the very first bubble is ingested. This procedure also tends to bring the vapor space pressure smoothly to atmospheric pressure just as the puncture is uncovered.

By comparison of the venting rate model to the air ingestion tests, the best value of the bubble volume factor mentioned above has been found to be 5.6. This gives an effective bubble diameter of about 1.8 times the puncture diameter, which agrees qualitatively with visual observations.

For very large punctures, and especially for long vertical punctures, the outflow may not completely cease during the air ingestion; that is, the bubbles may be ingested only over the top part of the puncture. This kind of ingestion was not observed in the smaller punctures used in the present tests, but if it does occur, the model described herein will provide a first approximation to the actual outflow rate.

II.4.2 Water Ingestion Models

When the puncture is below the water line, the tests have shown that water will be ingested whenever the net pressure

difference across the puncture approaches zero. Once started, water ingestion continued until the puncture was under water on both sides. In contrast to air ingestion where the outflow became intermittent, here the outflow remained steady but shared the puncture area with the water inflow. In other words, there was a water stream entering the tank and simultaneously a cargo liquid stream leaving the tank.

The models developed here assume the cargo and the ingested water do not mix or react chemically. This is a conservative assumption for many cargos, since the venting rate will be predicted to be larger than will actually occur. In any event, a model that included mixing or chemical reactions in the tank would be excessively complicated. Since the cargo and the liquid do not mix, the ingested water will displace a lighter cargo upward, thereby exposing more cargo to the puncture and increasing the static pressure at the puncture; see Figure II.2b. When the water is lighter than the cargo, the ingested water will float on top and thereby increase the static pressure at the puncture; see Figure II.2c. In both cases, the ingested water allows additional cargo to be discharged.

The driving force for water ingestion is the buoyancy (negative or positive) of the water relative to the cargo, which forces the water into the tank when the cargo outflow momentum is low (i.e., when the net positive pressure difference across the puncture is near zero). The tests showed that the water entering the tank under these conditions soon broke up into a stream of discrete droplets. Since an analysis of water ingestion could not be found in the literature, several new but approximate models were developed. The models contain one empirical constant that can be chosen to give better correlation to the test data. In summary, they are described as:

- Tank conditions for which the pressure differential across the puncture is zero are determined by an equation similar to equation (II.13) of the air ingestion model, but with the right hand side replaced by the hydrostatic head $g\rho_W (Z_W - Z_{Lh})$.
- Ingestion begins just prior to this condition of zero net ΔP, such that a small positive pressure differential, the magnitude of which is determined with the aid of the empirical constant mentioned earlier, will continue to force out cargo.
- The water inflow remains in a stream tube; this assumption allows the calculation of a ΔP acting on the water in the direction to force water into the tank.
- The puncture area is shared between the cargo outflow and the water inflow such that the inflow and outflow rates maintain the same pressure difference driving the cargo outflow as at the start of ingestion.

When the water is lighter than the cargo and the cargo static pressure at the puncture is equal to the outside pressure (atmospheric plus water hydrostatic head), the net pressure difference from the "inlet" to the "outlet" of the water streamtube mentioned above (Figure II.2c) can be calculated by considering the various static heads; the result is:

$$\Delta P_W = g (\rho_L - \rho_W) (Z_L - Z_{Lh}) \qquad \text{(II.14)}$$

which is just the buoyancy-induced pressure on a vertical water column of equal length. When the water is heavier than the cargo, the pressure differential is similarly:

$$\Delta P_W = g (\rho_W - \rho_L) (Z_{Lh} - Z_{WT}) \qquad \text{(II.15)}$$

In both cases, the water inflow rates are calculated by:

$$W_W = C_D A_{in} \rho_W \sqrt{2 \Delta P_W / \rho_W} \qquad \text{(II.16)}$$

where A_{in} is the part of the puncture occupied by the water stream. There is little or no change of phase (evaporation) of the liquid outflow during water ingestion since the tank pressure is nearly in equilibrium with the outside pressure; see equations (II.7b) and (II.8b). Thus, for simplicity, the cargo venting rate is calculated using an incompressible flow relation. The water inflow rate is supposed to be just large enough to maintain the original net ΔP at the time when ingestion started, so the cargo outflow rate is:

$$W_{Lo} = C_D A_{out} \rho_L \left\{ 2 \left[(P_{Ti} - P_{T,Eq.}) / \rho_L + g\,(Z_{Li} - Z_{L.Eq.}) \right] / K \right\}^{1/2} \qquad \text{(II.17)}$$

where $P_{T,Eq.}$ and $Z_{L,Eq.}$ are the values of P_T and Z_L which first satisfy the water ingestion form of equation (II.13). P_{Ti} and Z_{Li} are values at some slightly earlier time; in the computerized model, these correspond to the values at the time step preceding the start of water ingestion. The actual ΔP across the puncture may be only a fraction of the value $(P_{Ti} - P_{T,Eq.})/\rho_L + g\,(Z_{Li} - Z_{L,Eq.})$ selected by the computer scheme. Thus, an empirical constant K is inserted in equation (II.17); the best value obtained from the test comparisons is K = 83. It will be shown later that there is reason to believe that K = 83 is a universal value, and not just a value specific to a given test and computer prediction.

When the ingested water is lighter than the cargo, it floats on the liquid surface and suppresses any further evaporation. When it is heavier and thus sinks, evaporation is possible, but it is neglected in the models because the energy balances needed to predict temperature changes become much more complicated. In effect, the cargo is treated as an incompressible liquid and a non-condensable gas after water is ingested.

As mentioned earlier, the inflow rate of water is adjusted so as to maintain the pressure differential driving the cargo outflow. When the <u>water is heavier than the cargo</u> (Figure

II.2b), this merely requires that the two volumetric flow rates be equal so that Z_L remains constant; in other words

$$W_w = \rho_w W_{Lo} / \rho_L \tag{II.18}$$

Equations (II.16), (II.17), and (II.18) are all made compatible by allocating the puncture area between the two streams as:

$$A_{in} + A_{out} = A_p \tag{II.19}$$

These equations are sufficient to determine all the flow rates.

When the <u>water is lighter than the cargo</u> (Figure II.2c), the relation between W_w and W_{Lo} depends on whether the relief valve is operable. When it is, the vapor space pressure remains constant. Thus, to maintain a constant ΔP across the puncture, the weight of the water ingested must equal the weight of the cargo discharged, for otherwise the hydrostatic head above the puncture would change. The flow relation, consequently, is

$$W_w = W_{Lo} \tag{II.20a}$$

On the other hand, when the relief valve is jammed, the conditions specified by equation (II.20a) would compress the vapor space gas since a larger volume of water would be admitted than the volume of cargo discharged. Thus, the increase in P_T and the hydrostatic pressure changes must be balanced in order to hold constant the ΔP driving the water outflow. The appropriate relation is derived by expressing the ΔP at the puncture in terms of the vapor space compression and the changes in water and cargo levels; the result, as shown in Appendix A, is:

$$W_w = W_{Lo} \left\{ \frac{g\,(Z_T - Z_{WT}) + \gamma_m P_T / \rho_L}{g\,(Z_T - Z_{WT}) + \gamma_m P_T / \rho_W} \right\} \tag{II.20b}$$

Equations (II.13) - (II.20) constitute the models of water ingestion for those cases where some cargo liquid is discharged

prior to the start of ingestion. There are also situations where water can be ingested immediately upon puncturing the tank. This would occur whenever

$$P_{Ti} - P_{atm} + g\rho_L (Z_{Li} - Z_{Lh}) < g\rho_W (Z_W - Z_{Lh}) \qquad \text{(II.21)}$$

For these conditions, cargo would never be discharged unless water ingestion permits it.

When $\rho_W < \rho_L$, it is assumed that water will enter the tank and rise to the top without any cargo being discharged, until the tank pressure at the puncture is equal to the outside pressure:

$$P_T - P_{atm} + g\rho_W (Z_{WT,Eq.} - Z_{Li}) + g\rho_L (Z_{Li} - Z_{Lh}) = g\rho_W (Z_W - Z_{Lh}) \qquad \text{(II.22)}$$

Of course, if the required level of water $Z_{WT,Eq.}$ is greater than the elevation of the top of the tank, the tank will fill up with water before equation (II.22) is satisfied; this case is modeled separately. If $Z_{WT,Eq.} < Z_T$, water will continue to flow into the tank, but now cargo will be discharged since there is a net positive ΔP across the puncture. At this point, the venting model is the same as for the similar water ingestion models described earlier, although the cargo outflow rate equation can be simplified, as shown in Appendix A, to give:

$$W_{Lo} = C_D A_{out} \rho_L \sqrt{0.2g (Z_{WT,Eq.} - Z_{Lh})/K} \qquad \text{(II.23)}$$

$Z_{WT,Eq.}$ can exceed Z_T when the relief valve is operable, and P_T does not increase as the water enters. When this occurs, it is assumed that the water completely fills up the vapor space. The pressure thereafter in the vanishingly small volume between the top of the tank and the water is assumed to remain constant at the initial value maintained by the relief valve. Thus, as further water enters in an attempt to satisfy

equation (II.22), cargo will be forced out at the same volumetric flow rate. For this case, there is a net ΔP across the puncture forcing water into the tank, so

$$W_W = C_D A_{in} \rho_W \left\{ 2 \left[(P_{atm} - P_{Ti} / \rho_W + g (Z_W - Z_T) \right. \right.$$

$$\left. \left. - g (\rho_L - \rho_W) (Z_L - Z_{Lh}) \right] \right\}^{1/2} \qquad \text{(II.24a)}$$

and

$$W_{Lo} = \rho_L W_W / \rho_W \qquad \text{(II.24b)}$$

There are no other relations available to determine the way the puncture area is shared, so it is assumed that $A_{in} = A_{out} = A_p/2$.

When the relief valve is jammed shut, the vapor space pressure will increase as the water enters, and the condition that $Z_{WT,Eq.} \geq Z_T$ is impossible. For this case, equation (II.22) must be solved simultaneously with the relation between vapor space volume and pressure:

$$P_T = P_{Ti} \left(\frac{Z_T - Z_{Li}}{Z_T - Z_{WT,Eq.}} \right)^{\gamma_m} \qquad \text{(II.25)}$$

where the subscript "i" denotes the initial conditions.

When $\rho_W > \rho_L$, the water initially ingested into the tank will lift the cargo until there is a hydrostatic balance at the puncture. Since the original depth of cargo is Z_{Li}, the equilibrium relation is

$$P_T - P_{atm} + g\rho_L (Z_{Li} + Z_{WT,Eq.} - Z_{Lh}) = g\rho_W (Z_W - Z_{Lh}) \qquad \text{(II.26)}$$

where $Z_{Li} + Z_{WT,Eq.}$ is the new elevation of the cargo surface. Assuming for the moment that (1) $Z_{Li} + Z_{WT,Eq.} < Z_T$ (i.e., the new liquid level is below the top of the tank), and (2) the water in the tank does not cover the vent, further water will

be ingested, but now cargo will be discharged at the same volumetric rate. The model for this kind of venting is the same as the analogous models described earlier, except again it must be assumed that $A_{in} = A_{out} = A_p/2$. Ingestion will continue until the puncture is covered by water on both sides. If the water initially covers the vent, cargo is never discharged. If $Z_{Li} + Z_{WT,Eq.} > Z_T$, which can occur only when the relief valve is operable, it is assumed that the cargo is lifted entirely to the top of the tank and the vapor space pressure remains at its initial value. Then, as further water is ingested, cargo is discharged at the same volumetric flow rate. The water inflow rate is then given by

$$W_W = C_D A_{in} \rho_W \left\{ 2 \left[(P_{atm} - P_{Ti})/\rho_W + g\,(Z_W - Z_{Lh}) - g\,(\rho_L/\rho_W)\,(Z_T - Z_{Lh}) \right] \right\}^{1/2} \qquad \text{(II.27)}$$

which is based on the net ΔP from inside to outside at the center of the puncture. When the relief valve is jammed shut, an expression analogous to equation (II.25) is used to compute $Z_{WT,Eq.}$.

This completes all the water ingestion models.

II.5 Choked Flow Models

Some cargos (e.g., butane) have vapor pressures at normal temperatures that are substantially higher than atmospheric and are carried in pressurized tanks. If one of these tanks is punctured, the pressure differential across the opening may be so large that the outflow velocity is limited by the speed of sound [5]; in other words, the flow is "choked" to some lower value than that predicted by the models described in II.2, all of which assume that the pressure in the outflow stream at the puncture exit is the outside ambient pressure. For these cases, choked flow models are developed.

For venting of a gas, the limiting exit pressure for choked flow is [5]:

$$P_c = P_T \left(\frac{2}{\gamma_m + 1}\right)^{\frac{\gamma_m}{\gamma_m - 1}} \qquad \text{(II.28)}$$

If the calculated P_c is greater than ambient (atmospheric, plus water hydrostatic head if the puncture is submerged), the outflow will be choked, and P_c must be used in equation (II.9a) instead of P_∞ to compute W_{VO}. As the vapor continues to vent, P_T will gradually decrease until eventually $P_c = P_\infty$; at this point, the outflow is no longer choked, and equation (II.9a) can be used directly. Note that equation (II.28) considers the effects of two-phase flow for vapor as being negligible.

Ordinarily, flow of a liquid cannot be choked because of the very high speed of sound for liquids. For a volatile liquid, however, the change in phase of the outflow can easily lower the speed of sound to a fairly small value. The exit conditions for choked flow of a volatile liquid can be determined by maximizing the mass flow per unit area:

$$\frac{\dot{m}_{Lo}}{C_D A_o} = [2(h_L - h_{Lc} - x_c \lambda_c)]^{1/2} \Big/ [v_{Lc} + \beta x_c (v_{Vc} - v_{Lc})] \qquad \text{(II.29)}$$

where x_c represents the relative mass fraction of vapor in the outflow. (The static head above the puncture, $\rho g_L (Z_L - Z_{Lh})$, is neglected in this equation, since it should be small compared to the tank pressure P_V whenever choked flow is likely.) The maximum of equation (II.29) corresponds to

$$\frac{h_L - h_{Lc} - x_c \lambda_c}{v_{Lc} + \beta x_c (v_{Vc} - v_{Lc})} = -\frac{1}{2} \left\{ \frac{\frac{d}{dT_c}(h_{Lc} + x_c \lambda_c)}{\frac{d}{dT_c}[v_{Lc} + \beta x_c (v_{Vc} - v_{Lc})]} \right\} \qquad \text{(II.30)}$$

Equation (II.30) can be solved numerically using the known cargo pressure and temperature to determine the choked flow exit temperature T_c and corresponding saturation pressure, P_c. If this pressure is greater than P_∞, the flow is choked, and

these values of T_c and P_c must be used in equations (II.7) to compute W_{LO}. As the liquid vents, P_T may eventually decrease to the point where the exit pressure P_c required to choke the flow is smaller than P_∞; after this point, equations (II.7) can be used directly. Depending on the saturation pressure of the liquid, however, it is entirely possible for the liquid flow to remain choked throughout.

The choked flow model given by equations (II.29) and (II.30), although similar to that described in the Interim Report [3], assumes equilibrium flow rather than attempting to incorporate nonequilibrium effects [10,11] as suggested in [3]. The assumption of equilibrium flow is in general agreement with the assumptions used for nonchoked flows.

In the computer code, equation (II.30) is solved by expanding the left hand side in powers of ΔT, where $T_c = T - \Delta T$. The derivatives on the right side are evaluated numerically by assuming two values for T_c. As shown in Appendix A, the temperature difference ΔT is then found from:

$$\Delta T = T\left\{-\frac{\beta v_V}{\lambda}[D] + \sqrt{\left(\frac{\beta v_V}{\lambda}[D]\right)^2 + \frac{4v_L[D]}{C_{PL}T}\left[1 - \frac{\beta v_V E}{\lambda}[D]\right]}\right\} \div \left\{2\left[1 - \frac{\beta v_V A}{\lambda}[D]\right]\right\} \quad \text{(II.31a)}$$

where [D] is the computed approximate value of the derivatives:

$$[D] = \frac{d}{dT_c}\left[C_{PL}(T - T_c) - x_c\lambda_c\right] \Big/ \frac{d}{dT_c}\left[v_{Lc}(1 - \beta x_c) + \beta x_c v_{Vc}\right] \quad \text{(II.31b)}$$

The parameter E is related to the saturation pressure correlation (see equation (II.33) of Section II.6) and is:

$$E = [B_o T/(C_o + T^*)^2] \ln 10 - 1.5 \quad \text{(II.31c)}$$

(T^* is in °C, to conform to the Chemical Properties File usage; all the other temperatures are °K.) One or two iterations of equations (II.31) have been shown to be sufficient to determine T_c.

II.6 Review of Chemical Properties File

The previous technical review [2] indicated that the thermodynamic data in the Chemical Properties File were in error in some cases and the temperature range covered by the correlating equations was not sufficient in other cases. These conclusions have been confirmed by the present review. Six representative chemicals, all of which might be transported in a state where phase changes can occur so that thermodynamic properties are important, were reviewed in detail to document any errors; these chemicals are: anhydrous ammonia, butane, chlorine, LNG, methyl alcohol, and propane.

Based on this review of the representative chemicals, the following conclusions have been drawn about the adequacy of the present Chemical Properties File for use in the venting rate model.

1. Correlating equations for liquid density and specific heat are slightly inaccurate, but probably acceptable.
2. Correlating equations for saturated vapor properties are probably not acceptable; in particular, the specific heat for saturated vapor (not superheated vapor) and the compressibility factor should be included.
3. Correlating equations for saturation pressure as a function of temperature are moderately inaccurate and can lead to inaccurate predictions of tank pressure during venting.
4. The single value of latent heat given for each chemical differs by as much as 20% from the true value over the range of applicable temperatures

needed in the venting rate model energy balance and flow equations.

Recommended correlations for the six reviewed chemicals, based on the indicated data sources, are given in Appendix B. The recommended correlations for latent heat are derived from the Clausius-Clapeyron equation, $\lambda = (T^{*} + 273.17)(v_V - v_L)(dP_V/dT)$, using the new correlations given for vapor compressibility, liquid density, vapor compressibility factor, and vapor pressure. Thus, a separate correlation for λ is not needed, since it can be computed from the included correlations by the relation

$$\lambda = ZRB_o \ln 10 \, [(T^* + 273.2)/(T^* + C_o)]^2 - 5.501 \times 10^{-4} B_o P_V (T^* + 273.2)/(T^* + C_o) \rho_L \qquad \text{(II.32)}$$

Here, B_o and C_o are constants in the vapor pressure correlation:

$$\log_{10} P_V = A_o - B_o/(T^* + C_o) \qquad \text{(II.33)}$$

(In both equations (II.32) and (II.33), the units of temperature T^* are °C.)

Nonvolatile cargos are usually transported at near atmospheric pressures. Venting of gas is therefore unlikely to be important, and there will be little or no change of phase during liquid venting. Under these restrictions, the liquid density is the only cargo property that is important. The present Chemical Property File data, consequently, are sufficiently accurate for these cases.

III. EXPERIMENTAL PROGRAM

There were three primary objectives of the test program:

1. Obtain data to evaluate the assumptions of the analytical models
2. Gain insight into air and water ingestion
3. Obtain discharge rate data for a variety of test conditions to validate the overall reliability of the venting rate model.

III.1 Scaling Considerations

All the tests were conducted using tanks that were much smaller than full scale. It was important, then, that the simulated cargos and the initial tank conditions be selected so as to fairly represent full scale venting behavior. The liquid/vapor properties and the test conditions needed to achieve the desired simulation were determined from a similitude analysis [12] in which the important cargo and tank parameters were arranged in various nondimensional groups. This analysis showed clearly that an exact simulation would be difficult to obtain. For example, the static head of liquid in the tank, $g\rho_L Z_L$, was reduced considerably in the tests in comparison to full scale. To obtain similarity between the pressure differentials driving the discharges would have required a reduction of both the tank vapor-space pressure and the atmospheric pressure in direct proportion to $g\rho_L Z_L$. Although it would have been feasible to use a simulated cargo whose vapor pressure was less than full scale in accordance with this scaling criterion, conducting the entire test in a vacuum chamber or other apparatus to reduce the atmospheric pressure would have been extremely difficult and expensive. For this reason, tests achieving exact similarity to some given prototype were not attempted. The correct overall phenomena were, however, represented fairly well, as will be described in the next section. Lack of exact similarity does not

seriously limit the validation of the analytical model because the model can be used to predict results for the conditions used in the tests and the predictions compared with these test results.

III.2 Summary of Tests

III.2.1 Test Series No. 1: Discharge Coefficients

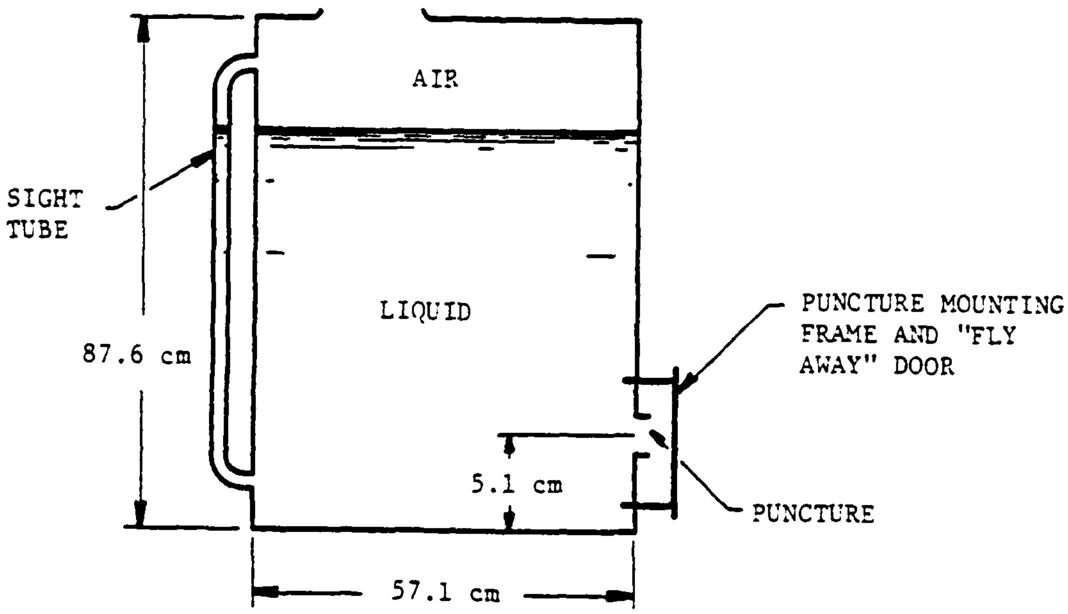
The original venting rate model [1] incorporated a fixed value of 0.8 for the discharge coefficient of the puncture. Since the predicted venting rate is directly proportional to the discharge coefficient, the first test series was designed to evaluate the implicit assumption that there is a negligible variation of C_D with puncture geometry, cargo properties, and discharge velocity.

The tests were conducted with an open cylindrical steel tank (Figure III.1a) having a diameter of 57.2 cm (22.5 in.), height of 87.6 cm (34.5 in.), and total capacity of 224.8 liters (59.4 gallons). A circular hole approximately 61 cm in diameter was machined in the wall of the tank near the bottom, around which a "picture frame" fixture was mounted flush to the outer surface. Simulated punctures were cut in sheet metal of about the same thickness as the tank wall (0.16 cm or 1/16 in.) and attached to the fixture, as indicated in Figure III.1a. In this way, three different puncture shapes could be readily tested using the same setup:

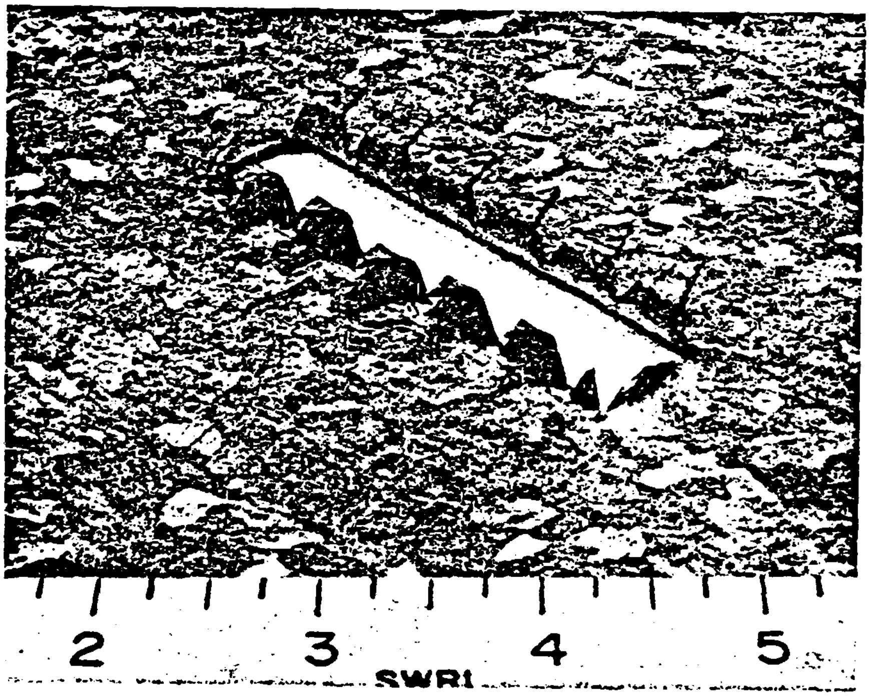
- circular
- horizontal rectangular (width/height = 5)
- vertical rectangular (height/width = 5)

Each puncture shape was tested with four different edge conditions:

- smooth
- jagged petals, all pushed inward uniformly
- jagged petals, all pushed outward uniformly
- jagged petals, pushed inward randomly



a) CYLINDRICAL STEEL TANK



b) TYPICAL SIMULATED PUNCTURE WITH JAGGED EDGE

FIGURE III.1. TEST APPARATUS FOR DETERMINATION OF DISCHARGE COEFFICIENTS

The smooth-edge punctures served as a baseline with which to compare the more realistic jagged punctures. A photograph of a typical jagged edge puncture is shown in Figure III.1b. Except for some preliminary tests, the open area of all the punctures was 11.4 cm^2, corresponding to circular holes of diameter 3.8 cm (1.5 in.) and to rectangular holes 7.55 cm by 1.51 cm (2.97 in. by 0.59 in.). To vary the Reynolds number of the discharge over a wide range, three different nonvolatile liquids were used: water, aqueous glycerine solution, and hydraulic oil. The densities and viscosities of these liquids are:

LIQUID	DENSITY (g/cm^3)	VISCOSITY (cp)
Water	0.998	0.98
40% Water - 60% Glycerine	1.157	8.63
Hydraulic Oil	0.878	64.90

For a given test, the tank was filled to a preselected level, generally 64.8 cm (35.5 in.) above the centerline of the puncture. The discharge was started by opening a quick-release valve. Liquid levels in the tank were measured visually during the test by a graduated sight tube attached to the tank, and flow times were measured with a stop watch. The tests were terminated when the liquid level was still above the puncture (generally 14.6 cm, or 5.75 in.). Each test was repeated at least three times. Test-to-test correlation was excellent, with the total discharge time never varying by more than 0.5 second.

As is the usual practice [13], the discharge coefficient was calculated by using Torricelli's equation to derive a relation between C_D and the test measurements:

$$C_D = \left(\frac{A_T}{A_p}\right)\left[\sqrt{2H_i/g} - \sqrt{2H_f/g}\right]\Big/\Delta t \qquad \text{(III.1)}$$

where H_i and H_f are the initial and final liquid depths in the

tank, and Δt is the total discharge time. A representative Reynolds number for the discharge is given by $\rho_L \sqrt{g(H_i + H_f) A_o}/\mu$, which is based on the discharge velocity corresponding to the average liquid depth.

Summaries of the test results are given in Table III.1. The discharge coefficient varied much more with geometry than with Reynolds number, at least for the Reynolds numbers that are of most interest. In particular, the horizontal or rectangular punctures with outward-pushed petals give C_D's that are 25% larger than for the other puncture geometries. The test values of C_D for the smooth-edge circular puncture agree reasonably well with published data [13] which show that C_D should decrease from about 0.68 to about 0.61 as the Reynolds number increases from about 1000 to over 100,000 or more; this favorable comparison validates the experimental procedure.

To summarize, these data show that a discharge coefficient of 0.65 should be adequate in practice for most punctures. The single exception to this recommendation would be a rectangular puncture having ragged edges pointing predominately outward; C_D for such a puncture averages about 0.825 for large Reynolds numbers. Note that the value of $C_D = 0.8$ used in the AMSHAH model [1] roughly corresponds to the singular exception of the tests.

The wall thicknesses of the tanks used in Test Series 2 and 3 were comparable to the hole diameters; for these holes, C_D was found to be about 0.73. It is believed that these kinds of punctures are not relevant to actual ship tank punctures, and so the data are not included in Table III.1.

III.2.2 Test Series No. 2 : Air and Water Ingestion Studies

The second series of tests was designed both to obtain insight about liquid discharge during air or water ingestion and to obtain quantitative data. In order to make visual observations, the tank was constructed of transparent acrylic

TABLE III.1. DISCHARGE COEFFICIENTS AS A FUNCTION OF PUNCTURE GEOMETRY AND REYNOLDS NUMBER

Representative Reynolds Numbers: Water = 96,000; Glycerine Solution = 12,600; Hydraulic Oil = 1275

Puncture Geometry	Edge Condition	Orientation	Discharge Coefficient		
			Water	Glycerine Solution	Hydraulic Oil
Circular	Smooth	--	0.650	0.663	0.648
Circular	Uniform Jagged Inward	--	0.622	0.663	0.608
Circular	Random Jagged Inward	--	0.577	0.577	0.571
Circular	Uniform Jagged Outward	--	0.619	0.620	0.627
Rectangular*	Smooth	Horizontal	0.625	0.645	0.652
Rectangular*	Smooth	Vertical	0.624	0.643	0.652
Rectangular*	Uniform Jagged Inward	Horizontal	0.629	0.629	0.611
Rectangular*	Uniform Jagged Inward	Vertical	0.626	0.608	0.609
Rectangular*	Random Jagged Inward	Horizontal	0.609	0.605	0.586
Rectangular*	Random Jagged Inward	Vertical	0.613	0.627	0.584
Rectangular*	Uniform Jagged Outward	Horizontal	0.826	0.798	0.739
Rectangular*	Uniform Jagged Outward	Vertical	0.828	0.802	0.741

*Aspect Ratio = 5:1

plastic. The tank, as sketched in Figure III.2, was a closed cylinder 27.6 cm (10.87 in.) in diameter and 61.0 cm (24 in.) high, with a total capacity of 36.5 liters (9.65 gallons). Two simulated circular punctures were drilled into the tank wall 4.4 cm (1.75 in.) above the bottom. The smaller puncture was 2.2 cm (0.875 in.) in diameter, and the larger was 3.2 cm (1.25 in.). Discharge coefficients for these punctures were determined to be 0.72 - 0.73, values higher than might be expected from Table III.1, but which are the result of the much larger wall thickness (about 1.2 cm) of this tank.

Air Ingestion Studies. For these tests, water was used as a convenient simulation of a nonvolatile cargo. Several preliminary tests were conducted to determine what vapor space vacuum pressures during the discharge could be held nearly constant by manually adjusting the simulated relief valve (Figure III.2).

The initial set of data-tests was conducted to determine the functional dependency of the starting point of air ingestion with liquid level and vapor space pressure. Within the accuracy of the measurements of liquid level and pressure, air ingestion was observed to begin when the tank pressure at the puncture (vapor space pressure plus hydrostatic) was within 0.25 KPa (1 in. of water) or less of atmospheric pressure; that is:

$$P_T - P_{atm} + g\rho_L\,(Z_L - Z_{Lh}) < 0.0025\,P_{atm} \qquad \text{(III.2)}$$

Since the vapor space pressure P_T could not be held exactly constant during a test, with pressure variations of $\pm$ 1 cm water not being uncommon, the value of the left hand side of equation (III.2) at the instant air ingestion started could not be calculated with exact certainty, but it was in the range of 0 to 0.0025 times P_{atm}.

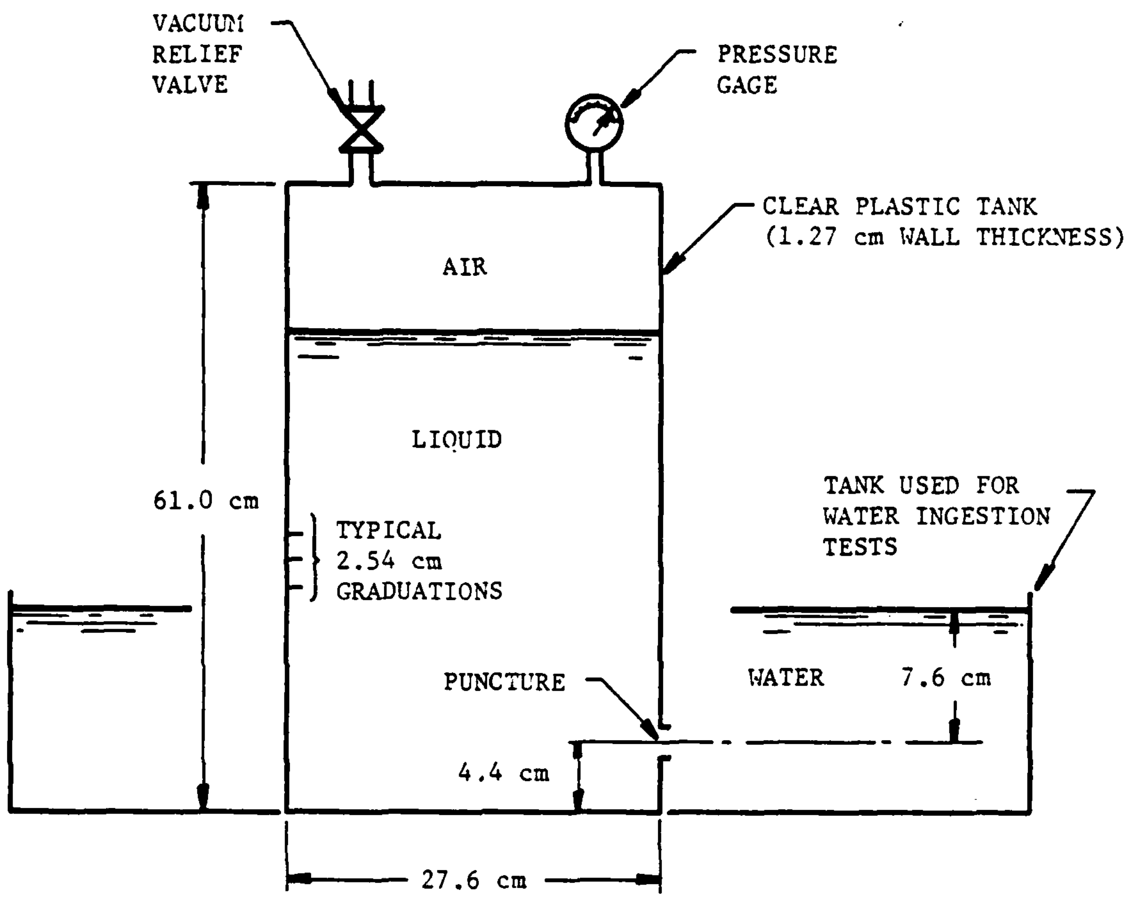


FIGURE III.2. TEST APPARATUS FOR AIR AND WATER INGESTION STUDIES

The next set of tests continued the venting past the point of air ingestion until the liquid level dropped to within 2.5 cm (1 in.) of the puncture centerline. These tests confirmed the assumptions used in developing the model of air-ingestion/intermittent outflow; that is: (1) the flow does not cease when $P_T - P_{atm} + g\rho_L (Z_L - Z_{Lh})$ first equals zero, if $Z_L > Z_{Lh}$; (2) air is ingested in the form of discrete bubbles, comparable in average diameter to about two or three times the puncture diameter; (3) during the time the bubble blocks the puncture, the outflow ceases; and (4) the vapor space pressure increases each time a bubble is ingested. Table III.2 summarizes the results of these tests. Again, each test was conducted at least three times, with excellent repeatability of the results (less than 1 second variation in discharge time).

Rise times of the bubbles were measured in several tests. The bubbles appeared to attain their terminal velocity very quickly; the average velocity was computed to be 50.2 cm/sec $\pm$ 4.5 cm/sec.

Water Ingestion Studies. For these tests, the tank was installed in a shallow but larger diameter sheet-metal tank, which was then filled with water until the puncture was submerged to a preselected depth. Three different liquids were tested: carbon tetrachloride, which is heavier than water; isopropyl alcohol, which is lighter than water; and aqueous glycerine, which is heavier than water. Carbon tetrachloride and isopropyl alcohol are both virtually immiscible with water, but water dissolves readily in aqueous glycerine. For these tests, the simulated safety relief valve was closed completely to emphasize the water ingestion aspects of the discharges.

The vapor space pressure during these tests dropped almost immediately to a vacuum about numerically equal to the hydrostatic head of the liquid, and water was ingested into the tank almost immediately. After passing through the puncture,

TABLE III.2. RESULTS OF AIR INGESTION STUDIES*

Puncture Diameter, cm	Vapor-Space Vacuum, cm of H_2O	Initial Water Height, cm	Air-Ingestion Water-Height, cm	Final Water Height, cm	Time to Air Ingestion, sec	Time to Final Height, sec
2.2	15.2	26.7	17.8	2.5	21.6	88.1
2.2	10.2	16.2	12.4	2.5	11.5	56.7
3.2	25.4	33.5	28.4	2.5	9.2	63.3
3.2	20.3	27.9	24.8	2.5	6.5	49.5

*Test liquid was water; all heights measured above puncture centerline.

the water stream broke up into droplets which rose to the surface for the carbon tetrachloride tests, or sank to the tank bottom for the isopropyl alcohol tests, or mixed with the tank liquid for the aqueous glycerine tests. The water ingestion continued thereafter until, for the carbon tetrachloride and isopropyl alcohol tests, the level of water in the tank covered the puncture. For the aqueous glycerine tests, the density of the tank liquid continuously decreased as a result of mixing with the ingested water, and the outflow decreased steadily; however, even after 45 minutes, some outflow was still observed. (The aqueous glycerine tests were conducted to study the basic phenomena of ingestion more completely; however, the venting rate model does not include any provisions for mixing of the ingested water with the cargo.) Table III.3 summarizes the results of the tests using carbon tetrachloride and isopropyl alcohol. For all these tests, the tank was submerged in water to a depth 7.6 cm (3 in.) above the centerline of the puncture, and only the smaller puncture (2.2 cm) was used.

The tank vacuum pressure during the carbon tetrachloride test slowly decreased as water was ingested, with the net effect being that the total pressure (vapor space + liquid head) at the puncture remained fairly constant. At the instant that water was first ingested, for example, the total pressure at the puncture was 11.4 cm of water, or just slightly greater than the hydrostatic head of water outside the tank (7.6 cm of water); as the carbon tetrachloride reached the top of the puncture, a point where the water level in the tank was 27.6 cm above the puncture, the total pressure at the puncture was 8.5 cm of water. It can be concluded that the mass flow rates of the water and the cargo adjusted themselves to maintain this constancy of pressure, and the analytical model of water ingestion for a cargo heavier than water is based upon this conclusion.

TABLE III.3. WATER INGESTION STUDIES

III.3a Carbon Tetrachloride, $\rho = 1.59\ g/cm^3$

Liquid Height, cm	Tank Pressure cm of H_2O Vacuum	Time, sec
27.9	33.0	∿ 0
22.9	30.5	110
17.8	27.9	245
12.7	24.9	380
7.6	22.1	510
2.5	20.3	635
top of puncture	19.1	665

At end of test, water height in tank = 27.6 cm

III.3b Isopropyl Alcohol, $\rho = 0.783\ g/cm^3$

Liquid Height, cm	Tank Pressure cm of H_2O Vacuum	Time, sec
27.9	12.7	∿ 0
27.3	12.7	613

At end of test, water height in tank = 5.6 cm, or level with puncture top.

For the isopropyl alcohol tests, the vapor space pressure remained nearly constant, as did the level of the isopropyl alcohol in the tank. The ingested water, which sank to the bottom of the tank, appeared to displace the tank liquid such that the inflow and outflow volumetric flow rates always remained equal, and neither the tank pressure nor the cargo liquid height varied greatly. In effect, all the cargo below the top of the puncture was discharged and replaced by water. (The slight drop of 0.6 cm in the level of the isopropyl alcohol may be due to its solubility in water, which is small but nonzero.) The analytical model for water ingestion into a tank containing a cargo lighter than water is based upon this conclusion about the flow rates.

III.2.3 Test Series No. 3: Discharge of Volatile Cargos

The final series of tests were designed to evaluate such thermodynamic phenomena for volatile cargos as liquid stratification, finite evaporation rates, and two-phase flow, and to obtain quantitative data for verification of the venting rate model.

A closed rectangular tank 30.5 cm by 30.5 cm (12 in. by 12 in.) and 61.0 cm (24 in.) high, made of 0.63 cm (0.25 in.) thick aluminum plate, with a total capacity of 56.6 liters (15 gallons), was used for these tests; see Figure III.3. The tank exterior was insulated by fiberglass 5 cm (2 in.) thick to approximate adiabatic test conditions. Two 600-watt heating tapes were attached to the wall to bring the simulated cargo to the desired temperature before a test. A small exterior pump continuously circulated the liquid in the tank during the pretest period to prevent any initial stratification; the spatial variation of liquid temperature was always kept below 0.27°C (0.5°F) prior to a test by this procedure.

Two simulated punctures, 0.32 cm (0.125 in.) and 2.2 cm (0.875 in.) diameter, were drilled into one wall near the vertical centerline and 7.6 cm (3 in.) above the bottom; most of

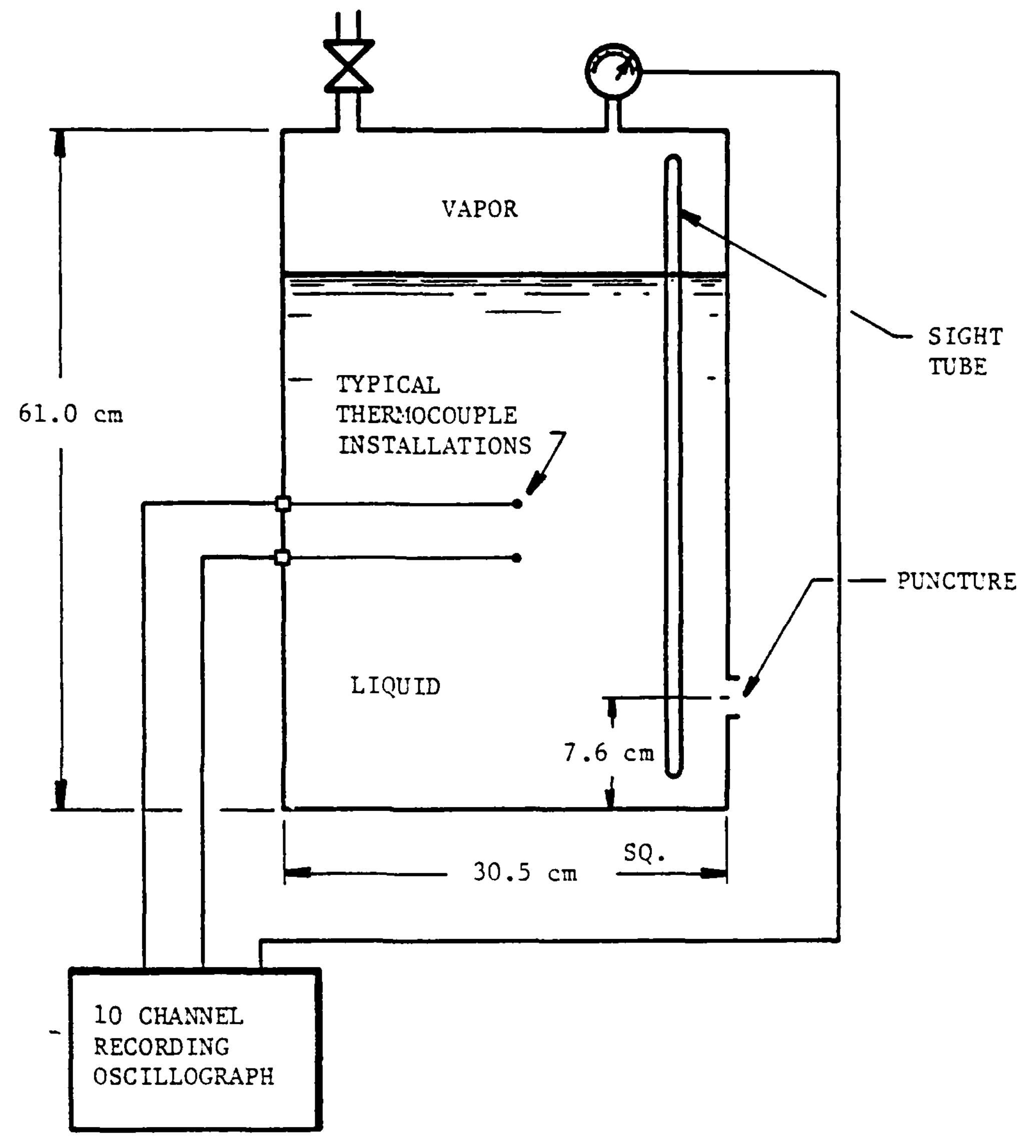


FIGURE III.3. INSULATED AND HEATED TEST TANK FOR DISCHARGE TESTS OF VOLATILE LIQUIDS

the testing was done with the larger puncture. A valve mounted on the tank top was used to vent vapor during the preliminary heating, and for some tests, as a simulated relief valve. Tank liquid levels were measured visually from a graduated sight tube, marked along each 2.54 cm (1.0 in.) of its length; in some tests, these measurements were verified, with excellent correlation, by thermocouple measurements as explained below.

The tank was instrumented with 20 Type J bayonet thermocouples inserted in one wall through drilled holes and extending to the vertical centerline of the tank; the vertical spacing of the holes was 2.54 cm. The vapor space pressure was measured with a diaphragm type of transducer (Validyne DP7). The thermocouple and pressure measurements were continuously recorded on a light beam, strip chart oscillograph (Honeywell Model 1858 Visicorder). A stop watch was used to measure discharge times; these measurements were verified by the timing marks on the strip chart.

Isopentane and methylene chloride (also called dichloromethane), both of which have boiling points slightly above room temperature at atmospheric pressure, were used in these tests as simulated volatile cargos. The properties of these liquids are shown in Table III.4. (Thermodynamic data on methy-methylene chloride are incomplete and somewhat contradictory; thus, these tabulations are not recommended for the Chemical Properties File without further verification.)

Test Preparations. Preliminary testing revealed that obtaining reproducible data for venting of volatile liquids would be difficult, primarily because of the difficulty in controlling the initial air content of the vapor space. Any small amount of air mixed with the vapor in the vapor space would result in an initial tank pressure that was larger than would be expected on the basis of saturation conditions for a pure vapor. This, in turn, would cause a rapid decrease in the tank pressure during venting. That is, the partial pressure of

TABLE III.4. SATURATED THERMODYNAMIC PROPERTIES OF ISOPENTANE AND METHYLENE CHLORIDE

P_v = saturation pressure (KPa); C_{PL}, $\overline{C}_{PV}$ = specific heats of saturated liquid and vapor (cal/g-°C); λ = latent heat of evaporation (cal/g); ρ_L = liquid density (g/cm^3); Z = vapor compressibility; and T = temperature (°C).

a. ISOPENTANE (molecular weight = 72.147) [14]

$$\log_{10} P_v = 5.9666 - 1045.87/(T + 236.18)$$
$$\rho_L = 0.6405 - 1.00255 \times 10^{-3}(T)$$
$$Z = 0.984 - 1.126 \times 10^{-4}(T) - 2.182 \times 10^{-6}(T^2)$$
$$C_{PL} = 0.5218 + 1.0584 \times 10^{-3}(T)$$
$$\overline{C}_{PV} = 0.360 + 2.12 \times 10^{-4}(T)$$
$$\lambda = [65.2257 - 7.4638 \times 10^{-2}(T) - 1.864 \times 10^{-4}(T^2)]\,\frac{(T+273.2)^2}{(T+236.18)^2} - 0.57530\, P_v\, (T+273.2)/\rho_L\, (T+236.18)^2$$

b. METHYLENE CHLORIDE (molecular weight = 84.93) [15]

$$\log_{10} P_v = 5.4971 - 822.48/(T+194.92)$$
$$\rho_L = 1.35 - 1.75 \times 10^{-3}(T)$$
$$Z = 0.9995 - 1.588 \times 10^{-3}(T) + 8.505 \times 10^{-6}(T^2)$$
$$C_{PL} = 0.285 + 3.50 \times 10^{-4}(T)$$
$$\overline{C}_{PV} = 0.129 - 1.651 \times 10^{-3}(T)$$
$$\lambda = [44.26 - 7.032 \times 10^{-2}(T) + 3.766 \times 10^{-4}(T^2)]\,\frac{(T+273.2)^2}{(T+194.92)^2} - 0.45242\, P_v\, (T+273.2)/\rho_L\, (T+194.92)^2$$

the constant mass of air decreased in accordance with the increase in vapor space volume as the liquid discharged. The partial pressure of the vapor, on the other hand, remained more nearly constant since its mass was increased by evaporation from the liquid surface at a rate that tended to compensate for the increase in vapor space volume. Depending upon the quantity of air initially contained in the vapor space, the drop in the vapor space pressure would lead to air ingestion through the puncture fairly quickly for some tests, while for other tests, with seemingly identical conditions, air ingestion would occur only near the end of the discharge, if at all. After this was realized, great care was taken to eliminate all the air from the vapor space, by the following procedure.

The tank was filled with liquid from the main reservoir until liquid flowed out the valve in the top of the tank. The valve was then closed, the filling halted, and the liquid heated until a small positive pressure existed. The valve was then opened to vent a liquid/vapor mixture, all the while continuing to heat the liquid to maintain a positive pressure in the tank and thus prevent air from entering through the valve. The boil-off of liquid was continued until the desired liquid level in the tank was obtained. The valve was then closed. The heating and the circulating of the liquid throughout the tank interior by the pump were continued, however, until the desired temperature and pressure conditions were obtained. Liquid (or vapor) discharge was then started by manually removing a rubber cork from the simulated puncture. This procedure usually led to reproducible tests, although some variation was still encountered occasionally, apparently because of air that became dissolved in the liquid isopentane and methylene chloride in their reservoirs. Altogether, nearly 40 tests were needed to obtain reliable venting data for each of the desired sets of initial conditions.

Liquid Stratification. Several of the tests were designed to evaluate the assumption that venting of the liquid would cause only a negligible degree of stratification.

Figures III.4 and III.5 show typical results of the thermocouple measurements for fairly rapid discharges of isopentane and methylene chloride through the 2.2-cm puncture. Some stratification is evident in the liquid near the liquid-vapor interface as a consequence of the heat transfer needed to provide the latent heat of vaporization, and there is a 1°-2°C temperature drop from the liquid to vapor. However, this small amount of stratification has a negligible effect on the energy content of the cargo, and the assumption that the temperature is uniform is acceptable for the purposes of formulating the energy balances, as will be shown later by the test and model comparisons. For slower discharge rates through the 0.32-cm puncture, stratification was even less noticeable.

The thermocouple strip-chart records, which clearly displayed the 1°-2°C temperature decrease at the liquid/vapor interface, provided a convenient check on the sight tube measurements of liquid level. The comparison of these two independent determinations was excellent.

Evaporation Rate. Figures III.6 and III.7 give typical results of vapor space pressure and liquid level for liquid discharges, for the same two tests given in Figures III.4 and III.5. The measured vapor space pressure decreased rapidly upon opening the puncture, and thereafter decreased more slowly. Also shown is the calculated saturation pressure of the liquid, based on the average liquid temperature estimated from the thermocouple records and on the liquid surface temperature; it can be seen that these two pressures differ very little, a further confirmation of the negligible effect of stratification. However, the actual vapor space pressure is significantly less than the saturation pressure, as it should be for the reasons discussed in Section II.3. A drop in vapor space pressure was observed even for the much slower venting through the 0.32-cm puncture, but the magnitude of the drop was much smaller, as shown for a typical case in Figure III.8.

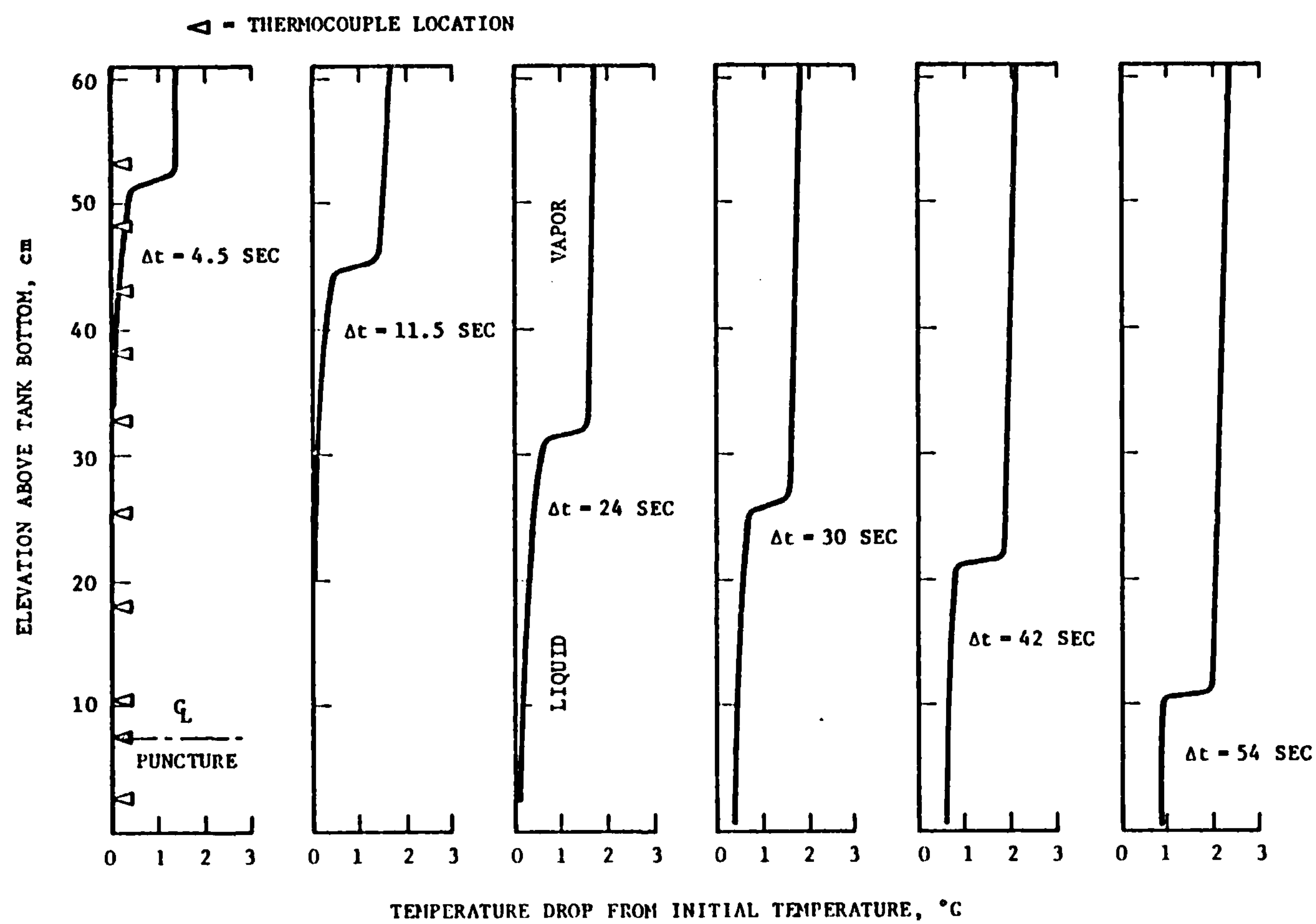


FIGURE III.4. TEMPERATURE STRATIFICATION FOR ISOPENTANE TEST NO. 6.
Z_{Li} = 56.2 cm; T_i = 29.2°C; $P_{Ti} - P_{atm}$ = 84 cm H_2O

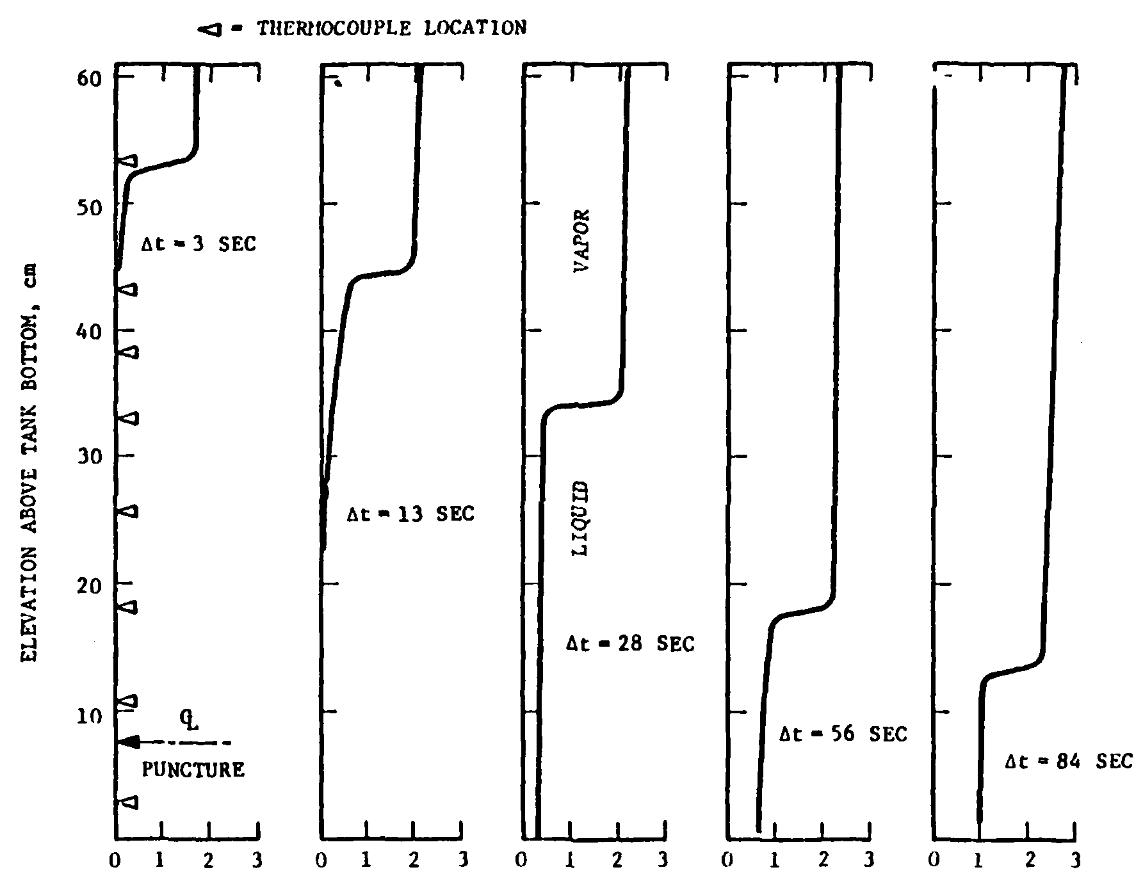


FIGURE III.5. TEMPERATURE STRATIFICATION FOR METHYLENE CHLORIDE TEST NO. 18. Z_{Li} = 54.6 cm; T_i = 41.4°C; $P_{T_i} - P_{atm}$ = 61 cm H_2O.

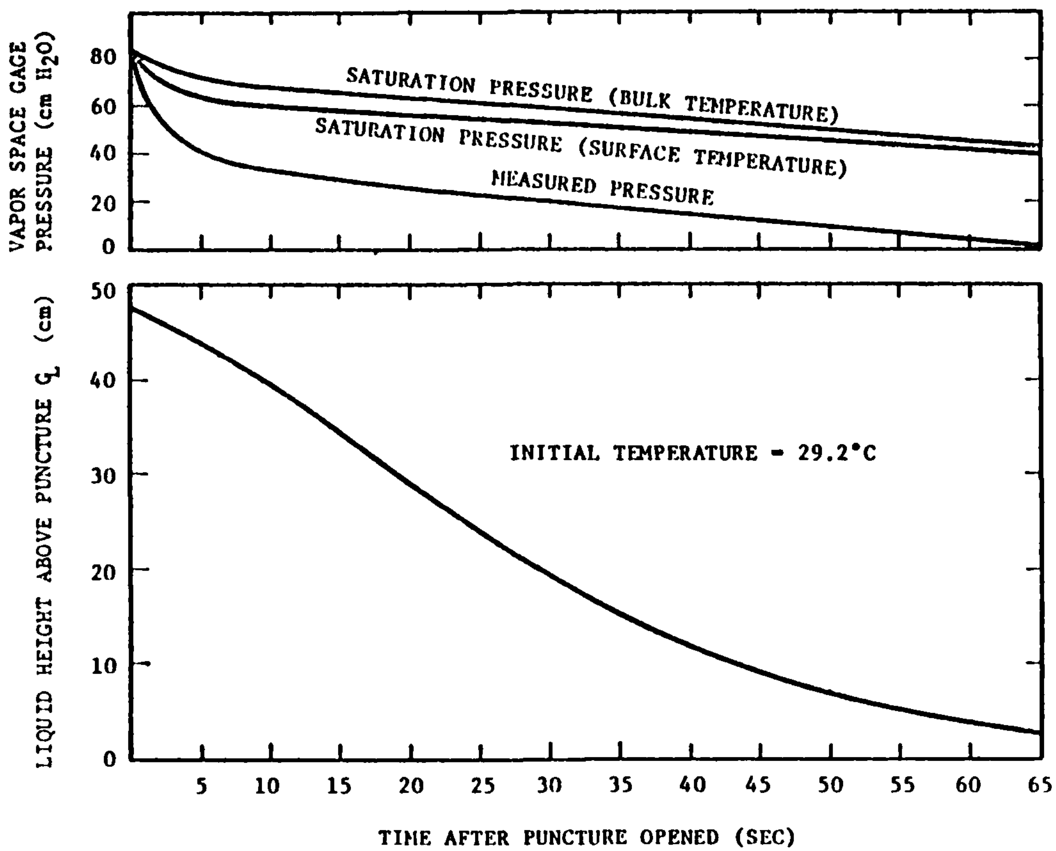


FIGURE III.6. DISCHARGE OF ISOPENTANE; PUNCTURE DIAMETER = 2.2 cm.
TEST NO. 6.

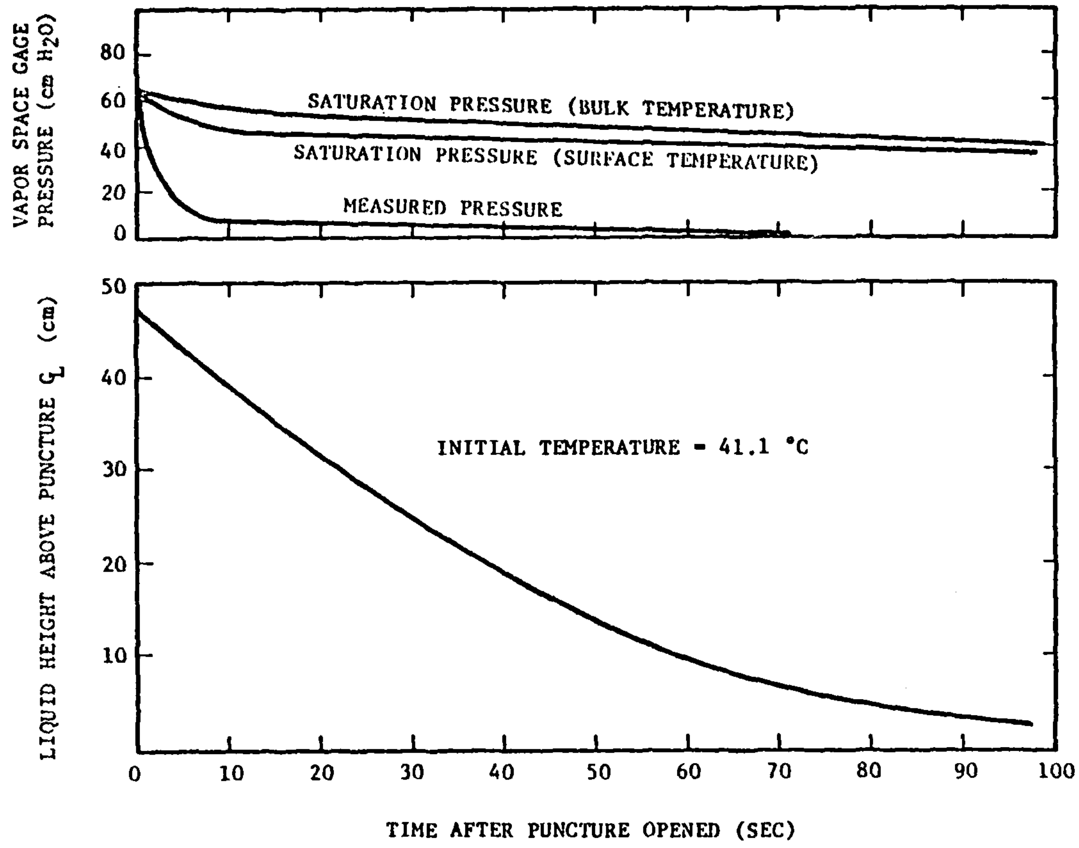


FIGURE III.7. DISCHARGE OF METHYLENE CHLORIDE; PUNCTURE DIAMETER = 2.2 cm. TEST NO. 18.

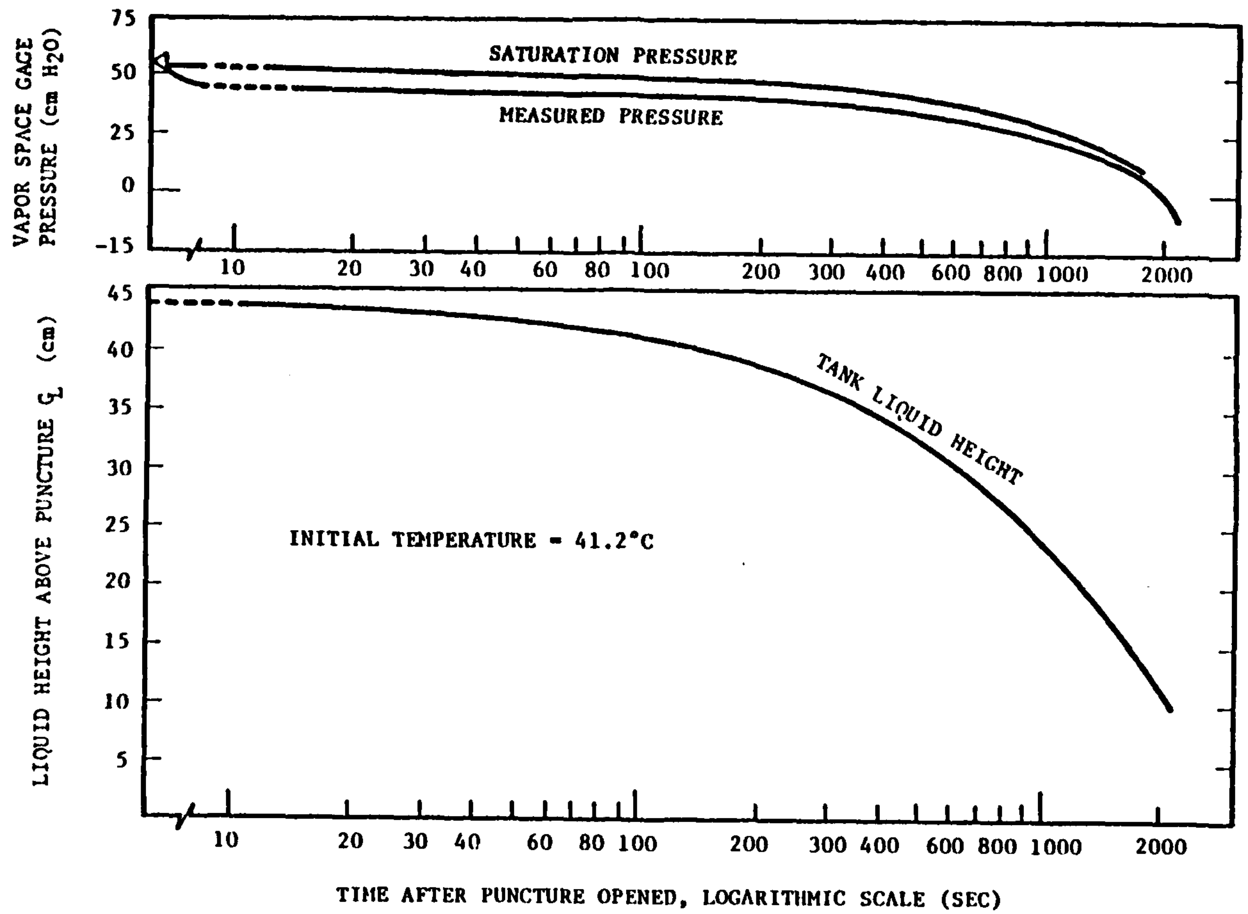


FIGURE III.8. DISCHARGE OF METHYLENE CHLORIDE; PUNCTURE DIAMETER = 0.32 cm. TEST NO. 22

The increase in the mass of vapor contained in the vapor space for these tests was computed by using the measured vapor space pressure and temperature records in conjunction with the measured liquid levels (i.e., vapor space volumes). The evaporation rate model described earlier in Section II.3 was also used to predict the evaporated mass, since $W_{e,sat}$ could be computed from the temperature measurements of the liquid, using the known saturation pressure vs temperature relation for the tested liquid to compute the needed saturation pressure. Comparisons of the model predictions (integrated with respect to time to give vapor mass change rather than evaporation rate) to the tests are shown in Figure III.9. As can be seen, the comparison is very close. These kinds of test and model results were used, in fact, to deduce the best value of the empirical constant (1.9) in equation (II.12). Predictions of the model given by equation (II.11) are also shown; these comparisons are much poorer.

It ought to be mentioned that there is some uncertainty in the accuracy of the adiabatic behavior of the liquid late in each test. The large thermal inertia of the test tank probably moderated the decrease of the liquid temperature somewhat, so that both the true "adiabatic" liquid temperature and, therefore, the saturation pressure should actually be slightly less near the end of the tests than are shown in Figures III.4 through III.8.

Two-Phase Flow. The tank liquid level data as a function of time were used both to evaluate the implicit assumption made in AMSHAH [1] that two-phase flow effects were negligible, and to determine the best correlating value of the empirical factor β in the present two-phase flow model.

For the test results shown in Figure III.8, the average discharge rate calculated from the test data is 23.2 g/sec for the 130 seconds required for the liquid level to drop 2.54 cm from an average level of 34.3 cm above the puncture centerline. Since the tank gage pressure at this time was

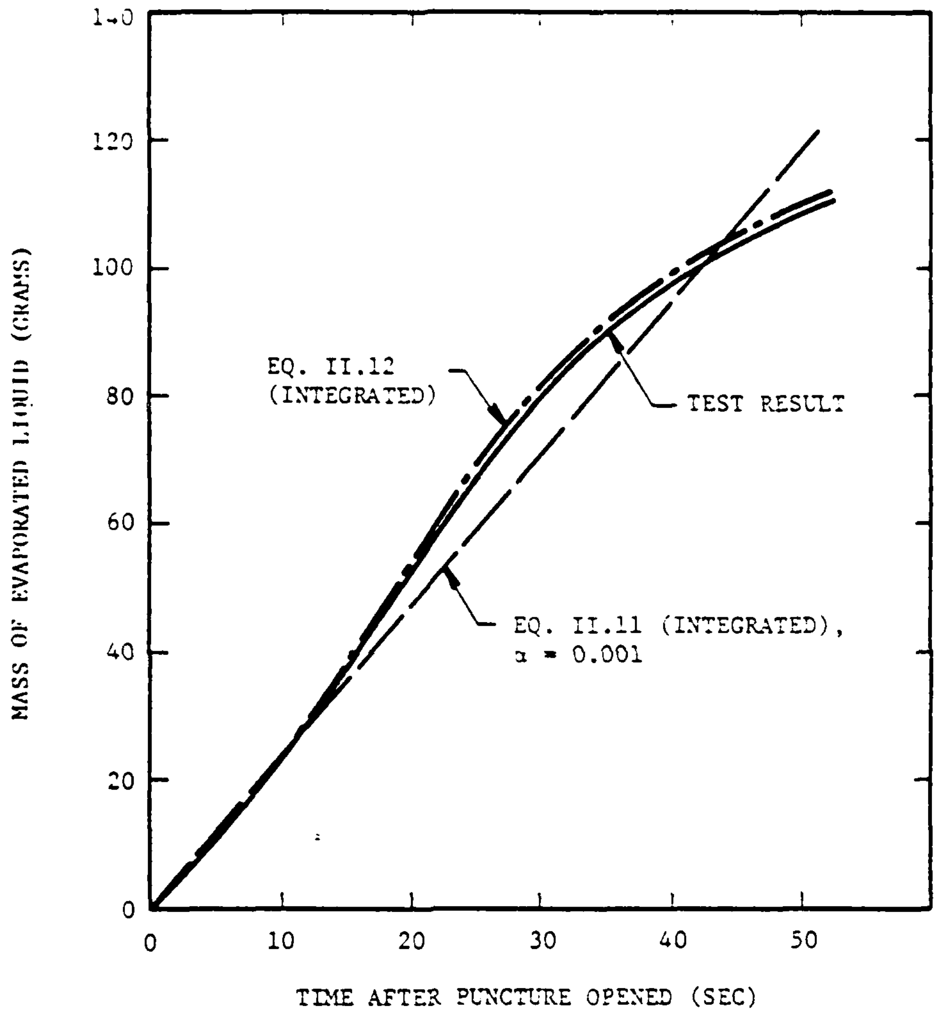


FIGURE III.9. COMPARISON OF PREDICTED AND MEASURED EVAPORATION. ISOPENTANE TEST NO. 6.

36.8 cm of water, the flow model used in [1] predicts that the discharge rate should be

$$W_{Lo} = 1.278 \frac{g}{cm^3} * 0.07917\ cm^2 * C_D * \left\{ 2 * 980.5 \frac{cm}{sec^2} * \left[\frac{36.8}{1.278} + 34.3\right] cm \right\}^{1/2} \qquad (III.3)$$

or 35.6 C_D g/sec. The discharge coefficient required by this model to agree with the measured W_{Lo} is 0.65, but the actual C_D (as determined by prior testing) is 0.73. The model therefore overpredicts the test results by 12%. Likewise, for the test data shown in Figure III.4, the single-phase flow model predicts a discharge rate of 708 g/sec (with C_D = 0.73) at the instant when the tank pressure is 30.5 cm H_2O and the liquid level is 35.5 cm, although the discharge rate calculated from the test data is about 600 g/sec; thus, the model also overpredicts this test by about 16%.

All the tests were analyzed at representative points to determine the best correlating value of β for the two-phase flow model (equations (II.7a) and (II.7b)). The best average value of β was found to be 0.12, and there was little test-to-test variation. For example, the discharge rates predicted by the model with β = 0.12 for the two tests described above are 23.7 g/sec and 636 g/sec, respectively, both in excellent agreement with the tests.*

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* For the methylene chloride test shown in Figure III.3, the test measurements at the indicated time were P_T = 101.60 KPa, P_{atm} = 98.0 KPa, T = 41.5°C, and $P_T - P_V$ = -7.5 cm H_2O = -0.75 KPa. The corresponding calculated liquid properties are ρ_L = 1.278 g/cm^3, T_s = 39.68°C, λ_s = 74.6 cal/g, v_{Vs} = 300.0 cm^3/g, and C_{PL} (average) = 0.299 cal/g-°C. From eq. (II.7b) with β = 0.12, v_{Lo} = 1.036 cm^3/g (or ρ_{Lo} = 0.965 g/cm^3). The discharge velocity (the radical in eq. (II.7a) is 425 cm/sec. Thus, W_{Lo} = 0.07917 * 0.73 * 425/1.036 = 23.7.

(Footnote continued on next page)

<u>Vapor Discharge</u>. Several tests were conducted in which only vapor was discharged, using the valve in the top of the tank as a simulated puncture. There was an initial blowdown of the tank pressure to very near atmospheric pressure, followed by a much slower discharge as the liquid remaining in the tank evaporated. These tests were not analyzed in detail for two reasons: test durations were so long that the tank processes could not validly be considered as adiabatic, and the test pressure instrumentation, which was designed primarily for liquid discharges, could not resolve the small pressure difference between the tank vapor space and the atmosphere which would be needed to make discharge rate comparisons with the model. It was noted, however, that the temperature of the vapor space was consistently much lower than the liquid as a result of the initial blowdown; a typical temperature difference was 17°C.

<u>Simultaneous Liquid and Vapor Discharge</u>. No unusual or unexpected phenomena were encountered during these tests. The vapor space pressure temperature again was nearly 17°C less than the liquid. These tests were not analyzed in detail for the same reasons given for the vapor discharge tests.

<u>Air Ingestion</u>. In a few tests, air was trapped in the vapor space deliberately during the tank filling process. In this way, a partial vacuum could be caused almost immediately after the start of the liquid discharge, and air was ingested through the puncture during most of the test. The air ingestion began at a tank pressure and liquid level that was in agreement with equation (III.2). No unusual or unexpected phenomena were observed, so the tests were not analyzed further.

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* For the isopentane test shown in Figure III.4, $P_T = 100.73$ KPa, $P_{atm} = 97.74$ KPa, $T = 28.9°C$, $P_T - P_V = -42.0$ cm H_2O = -4.11 KPa, $\rho_L = 0.611$ g/cm^3; $T_s = 26.83°C$, $\lambda_s = 84.7$ cal/g, $v_{Vs} = 346$ cm^3/g, and C_{PL} (average) = 0.551 cal/g-°C. The discharge specific volume = 2.181 cm^3/g and the discharge velocity = 490 cm/sec. Thus, $W_{Lo} = 3.879 * 0.73 * 490/2.181 = 636$ g/sec.

IV. VALIDATION OF MODEL

By using results of typical tests, all the empirical constants in the venting rate model have been determined by the methods discussed in Sections II and III. The predictive reliability of the overall model and its computerized solution are demonstrated in this section by comparison to results of all the test series.

IV.1 Discharge of Nonvolatile Liquids into Air; Operable Relief Valve

The discharge of a nonvolatile liquid into air was studied in Test Series No. 1 as a means of determining the variation of discharge coefficients with the shape of the puncture. With C_D supplied as input to the computerized model, the total time required to discharge the cargo initially above the puncture centerline was computed. The predicted venting times were virtually identical to the test results. For example, the predicted time was 66.5 seconds to discharge enough liquid to drop the level from 64.8 cm to 14.6 cm above the puncture centerline for the tank shown previously in Figure II.1. The average discharge time for a set of three tests was also 66.5 seconds.

IV.2 Discharge of Nonvolatile Liquids: Air Ingestion

Experimental results for liquid discharges in which air was ingested (the vacuum relief valve was jammed) were presented in Table II..2. All these data were analyzed in conjunction with predictions of the venting rate model to determine the best correlating value of the ingested air bubble volume factor. This value turned out to be 5.6; the implied average bubble diameter is therefore about 1.8 times the average open dimension of the puncture, which is in good agreement with the visual observations of bubble size.

Comparisons of a typical test of Test Series No. 2 (where the simulated cargo was water) and the predictions of the model are given below. In the test, the simulated relief valve was manually adjusted to maintain a pressure in the vapor space vacuum of 15.25 cm of water, so the relief set-point used in the prediction was also input as this value (i.e., 1.494 KPa).

INITIAL HEIGHT ABOVE PUNCTURE, cm		TIME TO INGESTION START, sec		HEIGHT AT INGESTION START, cm		TOTAL DISCHARGE TIME, sec	
Test	Model	Test	Model	Test	Model	Test	Model
26.7	26.7	21.6	22.3	17.8	21.3	88.1	86.0

As can be seen, the model-to-test comparison is excellent, both with respect to when ingestion begins and to the total time required to discharge the liquid.

IV.3 Discharge of Nonvolatile Liquids: Water Ingestion

Experimental results for the discharge of liquids when water was ingested were given in Table III.3. These tests were analyzed in conjunction with the venting rate model to determine the best correlating value of the empirical parameter K of the model (see, for example, equations (II.17)); the best overall correlation for all the tests was found to be given for K = 83.

When the simulated cargo was heavier than water, the model predicted the tests excellently, as shown in the table in the next page. In the tests, the relief valve was kept closed to create a vacuum pressure such that water was ingested almost immediately upon starting the discharge. In the model, nearly the same vacuum was predicted, with water being ingested after 0.8 second. For both the test and the model, the external water level was 12.7 cm above the puncture centerline. As can be seen, the model and the test are well correlated, including the trend and magnitude of the vapor space vacuum as a function of time.

INITIAL HEIGHT ABOVE PUNCTURE, cm		INITIAL VACUUM, cm H_2O		FINAL VACUUM, cm H_2O		TOTAL DISCHARGE TIME, sec	
Test	Model	Test	Model	Test	Model	Test	Model
27.9	27.9	33.0	28.9	17.8	13.1	665	641

By referring to equations (II.17), it can be seen that the model prediction of the discharge rate depends on P_{Ti} and Z_{Li}, the values of tank pressure and liquid height at the time increment just before water ingestion starts. For a given set of initial conditions, the numerical incrementing scheme will always arrive at these same values of P_{Ti} and Z_{Li}, and will predict the same values of $P_{T,Eq.}$ and $Z_{L,Eq.}$. For slightly different initial conditions, Z_{Li} and P_{Ti} would also be slightly different. On a percentage basis, however, the changes in $P_{Ti} - P_{T,Eq.}$ and $Z_{Li} - Z_{L,Eq.}$ would be substantial. Thus, the discharge rate prediction might change significantly for, say, a small change in the initial liquid level, although the actual discharge rate would be expected to change only slightly. Consequently, K would also need to be changed to bring the predictions into agreement, which is an undesirable result. To determine whether the predictions are in fact sensitive to small changes in the initial conditions, the initial liquid level in the computations was decreased by 0.1 cm, to 27.8 cm above the puncture. The corresponding change in $Z_{Li} - Z_{L,Eq.}$ was fifty percent. However, the predicted total discharge time changed by only 3 seconds, to 638 seconds, and the changes in the computed initial and final vacuum pressures were also negligible. The reason for the lack of sensitivity is that the slight increase of the initial vapor space volume resulted in a slight increase of P_{Ti}, which increased $P_{Ti} - P_{T,Eq.}$ just enough to cancel out the fifty percent decrease of $Z_{Li} - Z_{L,Eq.}$. It is concluded that there is very little sensitivity to slight changes in the initial conditions. The corollary to this conclusion is that the value K = 83 is general and not specific

to the particular values of Z_{Li} and P_{Ti} that result from a given set of initial conditions or the numerical solution technique.

Correlation of the model to the test results for cargos lighter than water was not as good. For example, for the isopropyl alcohol tests described in Section III, the measured time required for the ingested water level to reach the top of the puncture was 613 seconds, at which time the discharge ceased. The computed results were that 194 seconds are required to ingest enough water to cover the puncture; moreover, this prediction was not very sensitive at all to the value of K used in the range of 83 to 1000, so the value $K = 83$ selected from the tests with cargos heavier than water is also recommended for cargos lighter than water. The primary reason for the discrepancy in the model predictions is believed to be as follows: the conditions for water ingestion were met at the end of the first mass discharge incrementation cycle of the model. This meant that P_{Ti} (the pressure at the iteration preceding the start of ingestion) was selected as the initial vapor space pressure; that is, P_{Ti} was equal to atmospheric pressure. This value of tank pressure is the pressure that is subsequently maintained constant by the water ingestion model, rather than the 12.7 cm of water vacuum observed in the tests. The result is that the predicted discharge is too large. For a ship tank, the static head of the cargo above the puncture would be much larger than was used in these tests. Thus, the model would predict that a definite volume of liquid would be discharged before a vacuum large enough to cause water ingestion would be created. Therefore, the difficulty encountered in these predictions of the discharge time for the small tanks used in the present tests is probably not a serious one.

IV.4 Discharge of Volatile Liquids

Experimental results for the discharge of a volatile liquid were discussed in Section III. By analyzing the test

results, an evaporation rate model, as described in Section II.3, was formulated and the empirical constants of the model were determined. The empirical factor, β, in the model of two-phase flow was determined similarly. The entire venting rate model for volatile cargos is now compared to the tests.

Figure IV.1 shows a comparison between the predictions of liquid height, evaporated mass, and vapor space pressure, and representative results of a typical isopentane test taken from the strip-chart recordings. The predicted total time to discharge the cargo is about 63 seconds, compared to about 67 in the test; equally good agreement is apparent for the other parameters of interest. In particular, the vapor space pressure decreased with time in the same way as did the test; this indicates that the evaporation rate model includes the appropriate physical phenomena, even though the total mass evaporated into the vapor space is slightly overpredicted. Note that $P_T - P_{atm} \approx 0$ over most of the test and that P_{sat} always remains noticeably larger than P_{atm}. Consequently, basing the predictions on P_{sat} (as AMSHAH does) would overpredict the discharge rate, especially when the hydrostatic head was small, and might cause the onset of air or water ingestion, when they occur, to be missed entirely.

The discharge rate near the start of the test is slightly overpredicted because of the slight overprediction of the evap-evaporation rate, and this causes the prediction of tank liquid height to be less than the measured height throughout the rest of the discharge time. Note, however, that the discharge rate (i.e., the slope of the liquid height curve) is well predicted except for this initial discrepancy. Air ingestion was predicted to occur during the last 12 seconds of the discharge. The time at which air was first ingested in the test was difficult to determine since the tank was not transparent, but oscillations in the sight tube liquid level and in the pressure record became noticeable during the last 6 to 8 seconds, which indicate that air was being ingested for at least this period.

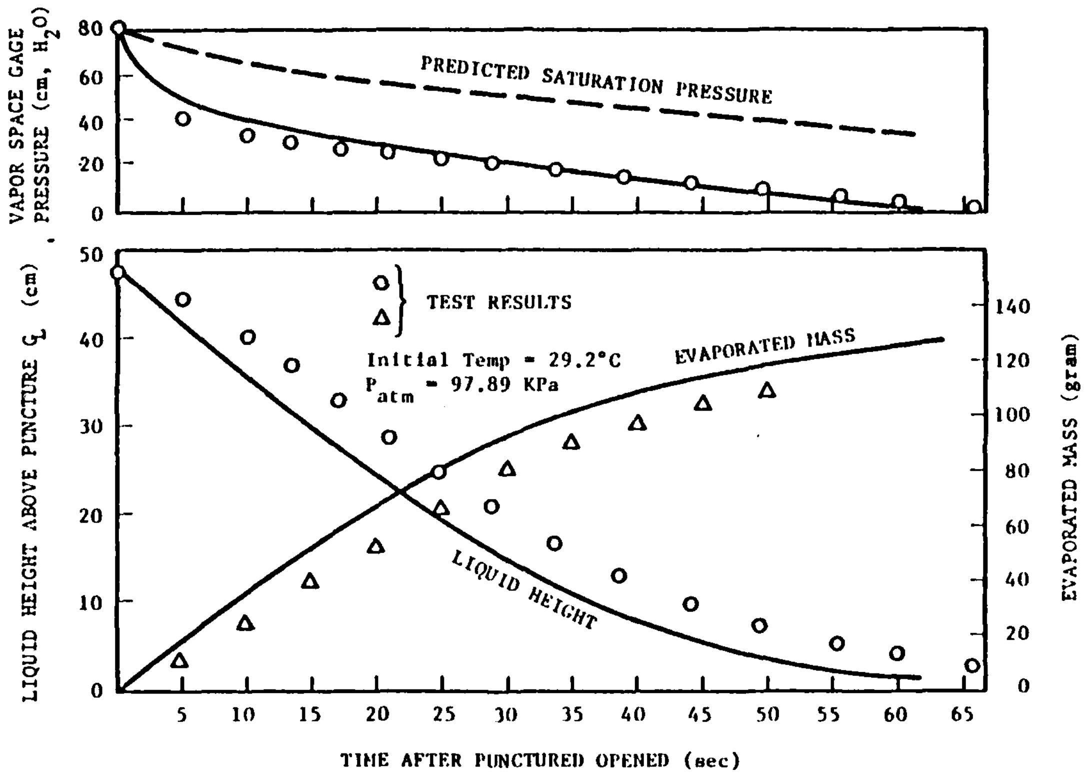

FIGURE IV.1. COMPARISON OF VENTING RATE MODEL AND TEST RESULTS FOR VENTING OF LIQUID ISOPENTANE; TEST NO. 6

Thus, the model and test are also in good agreement concerning air ingestion.

Figure IV.2 shows similar comparisons for a methylene chloride test. The predicted discharge time of 93 seconds compares well to the measured result of nearly 100 seconds. Predictions of the other phenomena also compare well, except that the magnitude of the initial rapid decrease of the vapor space pressure was underpredicted. This is perhaps the result in the test of the existence of a small quantity of air in the vapor space.

The initial temperature of the liquid for the predictions shown in both Figures IV.1 and IV.2 had to be adjusted slightly (less than 0.5°C) in comparison to the test measurement in order to bring the initial vapor space pressure into agreement with the tests. The experimental measurements of temperature, vapor space gage pressure, and local atmospheric pressure (all of which enter into the comparison of predicted and measured gage pressures) could have been in error by enough to explain this adjustment of initial temperature, but it is also possible that the industrial quality liquids used in the tests may not have had exactly the same vapor pressure versus temperature relation that was used in the model predictions.

IV.5 Other Validation Checks

Data from other tests, such as venting of vapor of volatile cargoes, were not reliable enough to serve as checks on the validity of the model. The computer model has been exercised, however, for all the various kinds of possible discharges of liquid and gas. These results have been verified against the analytical model by (1) single-point hand calculations and (2) reasonableness of predictions. As far as could be determined by these limited checks, the computerized model accurately reproduces these kinds of discharges.

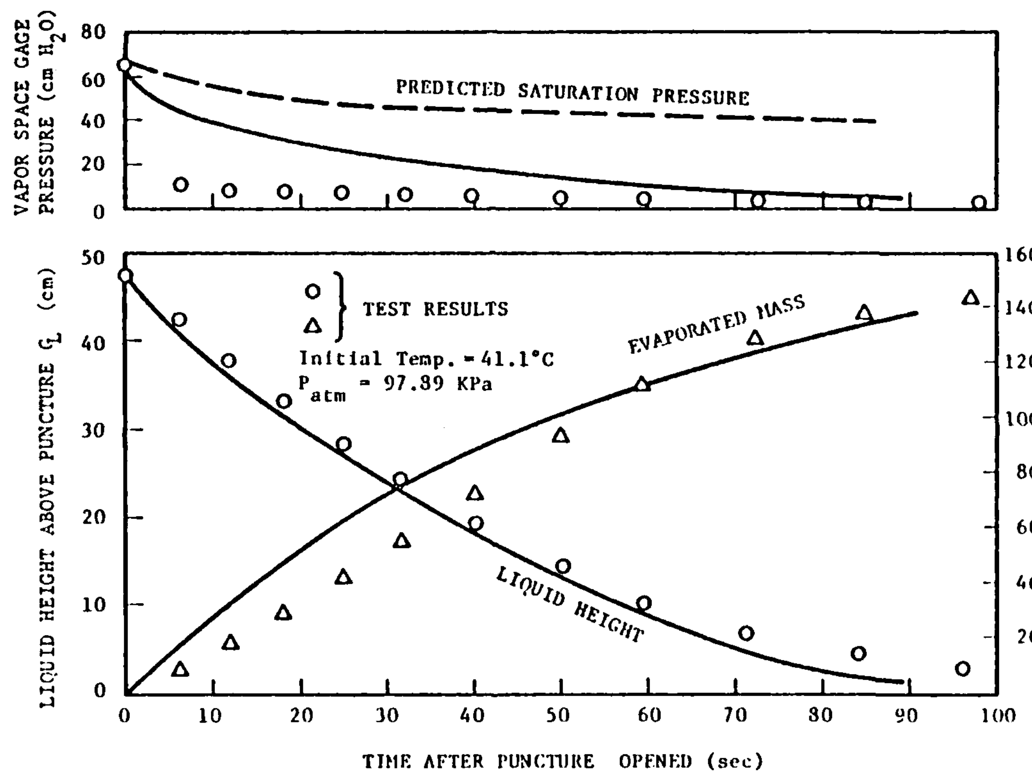

FIGURE IV.2. COMPARISON OF VENTING RATE MODEL AND TEST RESULTS FOR VENTING OF LIQUID METHYLENE CHLORIDE; TEST NO. 18

V. CONCLUSIONS

The Venting Rate Model previously developed by others for the Hazards Assessment Computer System has been completely reformulated. All errors in the basic equations have been corrected, and the limitations imposed by inappropriate assumptions have been removed. The revised model now covers nearly every practical combination of puncture location, cargo properties, intermittent outflows, and relief valve actuations. In summary, the revised model incorporates the following new features:

- o punctures above or below the waterline;
- o relief valve actuations;
- o the possibility of air in the vapor space;
- o simultaneous liquid and gas discharges;
- o phase changes during the discharge of volatile cargos;
- o choked flow of gases and volatile liquids;
- o air or water ingestion; and
- o realistic effects of evaporation within the tank.

Four of the submodels of the Venting Rate Model contain empirical constants whose "best" values have been determined by comparison to experimental data. Three of the constants are related to observable physical phenomena--the air bubble size factor of 5.6 in the air ingestion model, the constant 1.9 in the tank cargo evaporation model, and the constant $\beta = 0.12$ in the two-phase flow model. The fourth constant, $K = 83$, is used in the computerized solution of the water ingestion model. The relative importance of these constants in the predictions depends upon the type of cargo discharge encountered. In some cases the predictions are completely independent of the values of the constants. For example, when the relief valve is operable, air is admitted as needed to keep the vapor space pressure near atmospheric. Thus, air will not be ingested through

the puncture until the liquid discharge is nearly finished, and as a result the value of the bubble size factor is unimportant in the model predictions. Further, the vapor space pressure is controlled by the relief valve and not by evaporation into the vapor space, so the numerical constant in the evaporation model is likewise practically irrelevant. On the other hand, water can still be ingested, but only if the puncture is far enough below the waterline to overcome the hydrostatic head of the cargo. The onset of water ingestion will be considerably delayed, however, compared to a case when the relief valve is jammed shut. The effects of two-phase flow, and thus the value of β, are only important for discharges of cargos whose vapor pressure is greater than atmospheric and are carried in pressurized tanks. Otherwise the liquid discharge is predicted to be nearly incompressible, in agreement with observations. In any event, the two-phase flow model and the tank cargo evaporation model affect only the predicted time required for the discharge and not the total quantity of liquid cargo discharged. A faster discharge rate and a more conservative estimate of the hazard can be obtained by setting either or both of the empirical constants (β and 1.9) in these models to zero. The air and water ingestion models do influence the computation of the total liquid discharged, but the value of their empirical constants (the bubble size factor and $K = 83$) only change the discharge rate. A conservative estimate of the hazard can be obtained by decreasing the value of K (now equal to 83) in the water ingestion model or by increasing the value of the bubble size factor (now equal to 5.6) in the air ingestion model; either of these changes will increase the predicted discharge rate.

Predictions of the computerized Venting Rate Model have been compared to scale-model test results for many kinds of discharges. Generally good correlation of the model to the tests was found. In one sense, these good correlations do not necessarily represent a true verification of the model because

part of the data used in making the comparisons was used to determine the empirical constants of the various submodels. Usually, model verification requires a comparison of the model to an independent set of data taken under different experimental conditions from those which are used to determine the empirical constants. Because of the constraints in the scope of the project, it was not possible to conduct a separate set of experiments for the purpose of model verification. Therefore, an alternative technique was used.

Each submodel containing an empirical constant was first fitted to the relevant test data to determine the constant. For example, in determining β of the two-phase flow model, test measurements of liquid temperature, liquid level, vapor space pressure, etc., were used to make predictions of mass discharge rates, using the flow model alone; these were then compared to the measured discharge rates alone. Note that actual test data were used to determine β rather than predictions of liquid temperature, vapor space pressure, and the other required submodel inputs made from exercising the entire Venting Rate Model. Since only the flow submodel was used to find β, it was considered an appropriate test of the entire Venting Rate Model to input the initial conditions of the same experiments to compare its output to the actual test results. The good correlation of the entire model to test data thus does show that the energy balances have been formulated correctly, that the interaction of the energy balance with tank cargo evaporation has been modeled realistically, that the interaction of the air ingestion model with the vapor space pressure model has also been incorporated realistically, and so on. It can be concluded, then, that the Venting Rate Model has been verified to a significant degree. However, we would recommend that further experimentation and subsequent model validation be carried out.

The Chemical Properties File has been reviewed and found to be satisfactory for nonvolatile cargos. For volatile cargos, however, several additional correlations are required:

the compressibility and specific heat of saturated vapor, and the latent heat of evaporation. It also appears that the accuracy of the saturation pressure correlations should be improved.

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APPENDIX A. DERIVATION OF EQUATIONS

A.1 Tank Energy Balance

The tank contents are assumed to be "well stirred," and the temperature of the gas and the liquid are assumed to be equal. Considering a control volume around the liquid shown in Figure II.1, the general well-stirred reactor energy equation is:

$$\dot{Q}_{cv} + \sum \dot{m}_{in}\left(h_{in} + \frac{1}{2} V_{in}^2 + g\, z_{in}\right) = \dot{W}_{cv} + \frac{d\, E_{cv}}{dt}$$

$$+ \sum \dot{m}_{out}\left(h_{out} + \frac{1}{2} V_{out}^2 + g\, z_{out}\right) \qquad \text{(A.1)}$$

The work term $\dot{W}_{cv}$ includes the $P_T d\forall$ contribution of the moving boundaries. Equation (A.1) is specialized for adiabatic processes, $\dot{Q}_{cv} = 0$. The internal energy of the control volume is:

$$E_{cv} = M_L\left(u_L + \frac{1}{2} V_L^2 + g\, z_{L_{cm}}\right) \qquad \text{(A.2)}$$

where u_L is the liquid internal energy, V_L is the average liquid velocity in the tank and $z_{L_{cm}}$ is the vertical location of the liquid center of mass.

Stagnation enthalpies are defined as follows:

$$H_L = h_L + \frac{1}{2} V_L^2 = h_{Lo} + \frac{1}{2} V_{Lo}^2 \qquad \text{(A.3a)}$$

$$H_V = h_V + \frac{1}{2} V_G^2 = h_{Vo} + \frac{1}{2} V_{Go}^2 \qquad \text{(A.3b)}$$

$$H_A = h_{Ao} + \frac{1}{2} V_{Go}^2 \qquad \text{(A.3c)}$$

$$H_\infty = h_A + \frac{1}{2} V_A^2 \qquad \text{(A.3d)}$$

where the first two relations follow from the fact that the liquid (or the vapor) in the tank and in the discharge stream both have the same reservoir conditions. Since $u_L = h_L - P_T v_L$, equation (A.1) can be re-written as:

$$\frac{d}{dt}\left(M_L H_L + g\, Z_{L_{cm}}\right) - \frac{d}{dt}\left(P_T V_L\right) = -A_T P_T \frac{dZ_L}{dt}$$

$$- W_e\left(H_V + \frac{1}{2} V_e^2 - \frac{1}{2} V_G^2 + g\, Z_L\right) - W_{Lo}\left(H_L + g\, Z_{Lh}\right) \qquad \text{(A.4)}$$

An energy equation for a control volume around the vapor space can be written similarly:

$$\frac{d}{dt}\left[M_V H_V + M_A H_A + (M_A + M_V)\, g\, Z_{G_{cm}}\right] - \frac{d}{dt}\left(P_T V_V\right) =$$

$$A_T P_T \frac{dZ_L}{dt} + W_e\left(H_V + \frac{1}{2} V_e^2 - \frac{1}{2} V_G^2 + g\, Z_L\right) + W_A\left(H_\infty + g\, Z_T\right)$$

$$- W_{Vo}\left(H_V + g\, Z_{Gh}\right) - W_{Ao}\left(H_A + g\, Z_{Gh}\right) \qquad \text{(A.5)}$$

Here, the assumption has been made that the sum of the air and the vapor partial pressures is equal to the tank pressure, so that $P_A M_A v_A + P_V M_V v_V$ can be set equal to $P_A V_G + P_V V_G = (P_A + P_V)\, V_G = P_T V_G$.

Equations (A.4) and (A.5) can be combined by using conservation of mass (e.g., equations (II.2)) to eliminate the dM_V/dt and dM_A/dt terms, and by using the definition of the latent heat of vaporization:

$$H_V = H_L + \lambda + (V_G^2 - V_L^2)/2 \qquad \text{(A.6)}$$

The result is:

$$M_L \frac{dH_L}{dt} + M_V \frac{dH_V}{dt} + M_A \frac{dH_A}{dt} = \forall_T \frac{dP_T}{dt} + W_A (H_\infty - H_A)$$
$$+ \left[\lambda + \frac{1}{2} V_e^2 + (V_G^2 - V_L^2)/2\right] \left(\frac{dM_L}{dt} + W_{Lo}\right)$$
$$+ g \left\{ W_A Z_T - W_{Lo} Z_{Lh} - (W_{Vo} + W_{Ao}) Z_{Gh} \right.$$
$$\left. - \frac{d}{dt} [M_L Z_{Lcm} + (M_A + M_V) Z_{Gcm}] \right\} \tag{A.7}$$

According to the numerical examples given in [2], both the kinetic and potential energy terms are negligible during the discharge of a volatile substance. Thus, since dH/dt = dh/dt = C_p dT/dt when kinetic energy is negligible, equation (A.7) can be finally written as

$$(M_L C_{PL} + M_V \bar{C}_{PV} + M_A C_{PA}) \frac{dT}{dt} = \forall_T \left(\frac{dP_T}{dt}\right) + \lambda \left(\frac{dM_L}{dt} + W_{Lo}\right)$$
$$+ W_A C_{PA} (T_{air} - T) \tag{A.8}$$

which is equation (II.1) of the report.

A.2 Flow Equations for Volatile Substances

Considering an isentropic discharge of liquid from a saturated, or equilibrium, initial state, to an exit pressure P_∞ corresponding to a saturation temperature T_s, where the fluid is a liquid-vapor mixture, the thermodynamic quality of the exit mixture is:

$$x = \frac{s_{out} - s_{L_\infty}}{s_{V_s} - s_{L_s}} = \frac{s_L - s_{L_\infty}}{s_{V_s} - s_{L_s}} \tag{A.9}$$

where s_L is the entropy of the saturated liquid in the tank. (s_{out}) = s_{in} = s_L for an isentropic process). But

$$s_L - s_{Ls} = \int_{T_\infty}^{T} \frac{C_{PL} dT}{T} = C_{PL} \ln \frac{T}{T_s} \tag{A.10a}$$

and

$$s_{V_s} - s_{Ls} = \lambda_s/T_s \tag{A.10b}$$

Thus, the enthalpy change is:

$$h_{in} - h_{out} = h_{in} - [h_{Ls} + x\lambda_s] = C_{PL}(T - T_s) - C_{PL}T_s \ln \frac{T}{T_s} \tag{A.11}$$

If the liquid is compressed, i.e., if the tank pressure is greater than the saturation pressure, there is an additional enthalpy change, $v_L (P_T - P_V)$, when the pressure decreases in the exit stream to the saturation value. Altogether, then, the exit velocity, $\sqrt{2\Delta h + g\Delta Z}$, is

$$V_{Lo} = \left\{2\left[C_{PL}(T - T_s) - C_{PL}T_s \ln \frac{T}{T_s} + (P_T - P_V)/\rho_L + g(Z_L - Z_{Lh})\right]\right\}^{1/2} \tag{A.12}$$

The mass flow expression, equation (II.7a) follows directly.

The density of the exit mixture, for an isentropic discharge, would be similarly:

$$\rho_{Lo} = \frac{1}{v_{Lo}} = \left\{v_{Ls} + x(v_{Vs} - v_{Ls})\right\}^{-1}$$
$$= \left\{v_{Ls} + T_s C_{PL}(v_{Vs} - v_{Ls}) \ln \frac{T}{T_s}/\lambda_s\right\}^{-1} \tag{A.13}$$

However, previous tests (e.g., [25]) have shown that the evaporation from the liquid occurs mainly at the surface of the stream and is a function of the length-to-diameter ratio of the orifice. The net effect is that the exit mixture density has an average value that is larger than that predicted by equation (A.13). For that reason, the empirical factor β has been inserted in equation (II.7b). Presumably, a factor would also be needed .. the velocity relation, equation (A.12), but the results of [25] indicate otherwise.

The results for a vapor discharge can be derived similarly, but for a vapor the entropy change $s_V - s_{Vs}$ is

$$s_V - s_{Vs} = Z R \ln \frac{T}{T_s} - \overline{C}_{PV} \ln \frac{T}{T_s} \tag{A.14}$$

Equation (II.8a) then follows.

A.3 Evaporation Rate Correlation

By observing the trends exhibited by the tests, it seemed that the larger the evaporation rate was, the larger the discrepancy was between the measured tank pressure and the liquid saturation pressure. Consequently, a model of the form:

$$\Delta W_e = (W_e)_{sat} - (W_e)_{test} \propto (W_e)^n_{sat} \tag{A.15}$$

was assumed. $(W_e)_{sat}$ could be calculated for any test from the measured liquid temperatures and vapor space volumes; $(W_e)_{test}$ could also be computed from the measured vapor space pressures, temperatures, and volumes. The following table shows some typical numerical results (in g/sec):

Test No.	$(W_e)_{sat}$	$(W_e)_{test}$	ΔW_e	$\frac{\Delta W_e}{(W_e)_{sat}}$	$\frac{\Delta W_e}{(W_e)^2_{sat}}$	$\frac{\Delta W_e}{(W_e)^{5/4}_{sat}}$
6	2.43	2.31	0.12	0.050	0.020	0.039
20	3.27	3.17	0.10	0.031	0.009	0.023
22	0.079	0.078	0.0011	0.014	0.176	0.026

The value n = 1.25 best correlates the wide range of evaporation rates shown in the table. To make equation (A.15) dimensionally correct, the right hand side must be divided by $\{A_T \rho_L \sqrt{RT}\}^{1/4}$. The proportionality constant was found from linear regression to be 1.9.

A.4 Derivation of Water Ingestion Model Equations

Derivation of equation (II.20b). When the relief valve is jammed shut, the vapor space gas is compressed by the ingested water floating on the cargo; see Figure II.2c. Thus:

$$P_T = P_{Ti} \left(\frac{Z_T - Z_{Li}}{Z_T - Z_{WT}} \right)^{\gamma_m} \tag{A.16}$$

where $\gamma_m = 1$ for isothermal compression, and γ_m = ratio of gas specific heats for adiabatic compression.

The pressure differential at the puncture is:

$$\Delta P = P_T + g\rho_W (Z_{WT} - Z_L) + g\rho_L (Z_L - Z_{Lh}) - P_\infty \tag{A.17}$$

Since it is required that $d(\Delta P)/dt = 0$, equations (A.16) and (A.17) can be combined to give:

$$\left(\frac{\gamma_m P_T}{Z_T - Z_{WT}} \right) \frac{dZ_{WT}}{dt} + g\rho_W \left(\frac{dZ_{WT}}{dt} - \frac{dZ_L}{dt} \right) + g\rho_L \left(\frac{dZ_L}{dt} \right) = 0 \tag{A.18}$$

But $dZ_{WT}/dt = (W_W/\rho_W - W_{Lo}/\rho_L)/A_T$ and $dZ_L/dt = -W_{Lo}/\rho_L A_T$. Equation (II.20) is derived by substituting these relations into equation (A.18) and solving for W_W.

Derivation of equation (II.23). When $Z_{WT,Eq.} < Z_T$, the cargo outflow is assumed to begin when the water level in the tank is slightly greater than $Z_{WT,Eq.}$; in particular, it begins at

$$Z_{WT} = 1.1\,(Z_{WT,Eq.} - Z_{Lh}) + Z_{Lh} \tag{A.19}$$

This is analogous to the use of $P_{Ti} - P_{T,Eq.}$ and $Z_{Li} - Z_{L,Eq.}$ in equation (II.17), but here the ΔP at the puncture is just $Z_{WT} - Z_{Lh} - (Z_{WT,Eq.} - Z_{Lh}) = 0.1\,(Z_{WT,Eq.} - Z_{Lh})$. Equation (II.23) follows directly.

A.5 Derivation of Choked Flow Equations (II.31)

As shown previously in equations (A.9) and (A.10), the thermodynamic quality of the discharge mixture for an isentropic expansion to temperature T_c is:

$$x = C_{PL} T_c \ln \frac{T}{T_c} / \lambda_c \tag{A.20}$$

Making the substitution $T_c = T\left(1 - \frac{\Delta T}{T}\right)$, and expanding in powers of $\Delta T/T$ gives:

$$x\lambda_c = C_{PL}\Delta T \left[1 - \frac{1}{2}\left(\frac{\Delta T}{T}\right) + \ldots\right] \tag{A.21}$$

Likewise

$$h_L - h_{Lc} = C_{PL}\Delta T \tag{A.22}$$

The vapor density v_{Vc} can be written as:

$$v_{Vc} = \frac{ZRT_c}{P_c} = \frac{ZRT}{P} \frac{\left(1 - \frac{\Delta T}{T}\right)}{\left(1 - \frac{\Delta P}{P}\right)} \approx v_V \left(1 - \frac{\Delta T}{T}\right)\left(1 + \frac{\Delta P}{P} + \ldots\right) \tag{A.23}$$

From the Chemical Properties File, the pressure P is given by

$$\frac{\ln P}{\ln 10} = A - \frac{B}{(C + T^*)} \tag{A.24}$$

so

$$\frac{\Delta P}{P} \approx \ln 10 \left[\frac{B\,\Delta T}{(C + T^*)^2}\right] \tag{A.25}$$

Therefore, the product $x_c v_{Vc}$ can be expressed as

$$x_c v_{Vc} = \frac{C_{PL}\Delta T}{\lambda_c}\left[1 - \frac{1}{2}\left(\frac{\Delta T}{T}\right)\right] v_V \left\{1 + \frac{\Delta T}{T}\left[\frac{BT\,\ell n\,10}{(C + T^*)^2} - 1\right]\right\}$$

$$= \frac{C_{PL}\Delta T\, v_V}{\lambda_c}\left\{1 + \frac{\Delta T}{T}\left[\frac{BT\,\ell n\,10}{(C + T^*)^2} - \frac{3}{2}\right]\right\} \tag{A.26}$$

Since βx_c is generally small, the term $v_{Lc} - \beta x_c v_{Lc}$ in the denominator of equation (II.30) is approximated as $v_{Lc} \approx v_L$. Likewise, $\lambda_c \approx \lambda$, so altogether equation (II.30) can be written as:

$$\frac{\frac{1}{2}\, C_{PL}\left(\frac{\Delta T}{T}\right)^2}{v_L + \frac{\beta C_{PL} v_V T}{\lambda}\left(\frac{\Delta T}{T}\right)\left[1 + \frac{\Delta T}{T}\, E\right]} = -\frac{1}{2}\,[D] \tag{A.27}$$

where E and [D] are given by equations (II.31b) and (II.31c). Equation (A.27) is quadratic in $(\Delta T/T)$ and can be solved to give equation (II.31a).

APPENDIX B. CHEMICAL PROPERTIES FILE

Units are generally in the cgs system: pressure in multiples of 10^5 dyne/cm^2 = 10^3 N/m^2 = 1 KPa; specific heat in cal/gr-°C; latent heat in cal/gr; temperature in °C; and density in gr/cm^3. The temperature range of validity for the correlations generally correspond to vapor pressures from about 0.1 to 2 to 4 atmospheres. Maximum errors of the correlations with respect to the cited data sources are also given. Correlations from the present CPF are given in parentheses, as well as their maximum error over the same temperature range.

In most of the data sources, English units are used. The new correlations were initially developed therefore in English units and then converted to cgs. For the same reason, the English units correlations given in the CPF were reviewed and converted to cgs.

1. ANHYDROUS AMMONIA [16,17,18], molecular weight = 17.698

Range of validity: -40°C to 38°C (71.8 kPa to 1461 kPa)

- $\log_{10} P_V = 6.61724 - \dfrac{976.98}{T + 245.19}$; max. error = -0.73%

  $\left(= 7.1465 - \dfrac{1232.78}{T + 273.2}\right.$; max. error = 4.05%)

- $\rho_L = 0.6371 - 1.413 \times 10^{-3} T$; max. error = -0.29%

  ($= 0.6538 - 1.299 \times 10^{-2} T - 1.36 \times 10^{-5} T^2$; max. error = 2.43%)

- $Z = 0.932 - 1.647 \times 10^{-3} T - 1.215 \times 10^{-5} T^2$; max. error = 0

  ($= 1.0$; max. error = 17.4%)

- $C_{PL} = 1.104 + 1.20 \times 10^{-3} T$; max. error = 0.73%

  ($1.100 + 1.000 \times 10^{-3} T$; max. error = 1.56%,

- $\overline{C_{PV}} = 0.257 - 4.02 \times 10^{-3}T - 1.504 \times 10^{-5}T^2$; max. error = -2.61%)

  ($C_{PV} = 0.533 + 2.616 \times 10^{-3}T + 3.756 \times 10^{-7}T^2 + 1.644 \times 10^{-10}$; max. error = 449.9%)

- $\lambda = [244.37 - 0.432T - 1.1023 \times 10^{-3}T^2] \left(\frac{T + 273.2}{T + 245.2}\right)^2 - \frac{0.53741\, P_V\, (T + 273.2)}{(T + 245.2)^2 (0.6371 - 1.413 \times 10^{-3}T)}$; max. error = -0.31%

  (= 327.0 ; max. error = 18.82%)

2. BUTANE [15,16,18,19,20], molecular weight = 58.121

   Range of validity: -55°C to 43°C (6.9 kPa to 415 kPa)

- $\log_{10}P_V = 5.9496 - \frac{943.46}{T + 239.7}$; max. error ≈ 0.49%

  ($= 5.9545 - \frac{946.11}{T + 240}$; max. error = 0.76%)

- $\rho_L = 0.5952 - 9.267 \times 10^{-4}T$; max. error ≈ 0.14%

  ($= 0.6009 - 9.000 \times 10^{-4}T$; max. error = 1.37%)

- $Z = 0.95746 - 1.1405 \times 10^{-3}T - 1.0404 \times 10^{-5}T^2$; max. error = -0.38%

  (= 1.0 ; max. error = 12.55%)

- $C_{PL} = 0.5540 + 2.7378 \times 10^{-4}T + 1.5116 \times 10^{-5}T^2$; max. error = 1.64%

  ($= 0.5800 + 1.300 \times 10^{-3}T$; max. error = 8.02%)

- $\overline{C_{PV}} = 0.335$; max. error = 3.72%

  ($C_{PV} = 0.3811 + 1.150 \times 10^{-3}T - 6.384 \times 10^{-7}T^2 + 1.445 \times 10^{-10}T^3$; max. error = 28.38%)

- $\lambda = [71.069 - 8.4656 \times 10^{-2}T - 7.7226 \times 10^{-4}T^2]\left(\frac{T + 273.2}{T + 239.7}\right)^2$

  $- \dfrac{0.51897\,P_V\,(T + 273.2)}{(T + 239.7)^2(0.5952 - 9.267 \times 10^{-4}T}$; max. error = 1.57%

  (= 92.0 ; max. error = 13.58%)

3. CHLORINE [21], molecular weight = 70.91

   Range of validity: -51° to 38° (45 kPa to 1067 kPa)

- $\log_{10}P_v = 6.0540 - \dfrac{860.19}{T + 246.52}$; max. error = 0.16%

  (= $6.5425 - \dfrac{1086.11}{T + 273.17}$; max. error = 5.02%)

- $\rho_L = 1.4676 - 2.8738 \times 10^{-3}T$; max. error = 0.49%

  (= $1.4599 - 2.599 \times 10^{-3}T$; max. error = 0.93%)

- $Z = 0.948 - 1.3064 \times 10^{-3}T - 9.383 \times 10^{-6}T^2$; max. error = 0.10%

  (= 1.0 ; max. error = 11.5%)

- $C_{PL} = 0.2334 + 1.35 \times 10^{-4}T$; max. error = -2.05%

  (= $0.1200 + 5.00 \times 10^{-4}T$; max. error = -58.19%)

- $\overline{C_{PV}} = 0.0832 - 5.6571 \times 10^{-4}T - 4.3393 \times 10^{-6}T^2$; max. error = 0.61%

  ($C_{PV} = 0.1130 + 5.8933 \times 10^{-5}T - 9.166 \times 10^{-8}T^2$; max. error = 89.73%)

- $\lambda = [52.585 - 7.2465 \times 10^{-2}T - 5.2047 \times 10^{-4}T^2]\left(\frac{T + 273.2}{T + 246.52}\right)^2$

  $- \dfrac{0.47317\,P_V\,(T + 273.2)}{(T + 246.52)^2(1.4676 - 2.8738 \times 10^{-2}T)}$; max. error = -0.55%

  (= 68.72 ; max. error = 19.28%)

4. LNG* [15,13,19,22,23], molecular weight = 16.03

Range of validity: -177° to -153° (22.3 kPa to 202.5 kPa)

- $\log_{10} P_V = 5.7365 - \frac{389.89}{T + 266.0}$; max. error = -1.14%

  (= same)

- $\rho_L = 0.1833 - 1.665 \times 10^{-3} T$; max. error = 0%

  (= $0.1880 - 1.399 \times 10^{-3} T$; max. error = 1.98%)

- $Z = -2.5724 - 3.97015 \times 10^{-2} T - 1.10412 \times 10^{-4} T^2$; max. error = 0.45%)

  (= 1.0 ; max. error = 4.21%)

- $C_{PL} = 1.1995 + 2.2639 \times 10^{-3} T$; max. error = -0.57%

  (= $1.1961 + 2.1996 \times 10^{-3} T$; max. error = 1.33%)

- $\overline{C_{PV}} = 2.2639 + 1.0904 \times 10^{-2} T$; max. error = -4.48%

  ($C_{PV} = 0.5166 + 6.6838 \times 10^{-4} T + 5.311 \times 10^{-7} T^2$; max. error = 12.1%)

- $$\lambda = -[236.63 + 4.4238\,T + 1.23028 \times 10^{-2} T^2] \left(\frac{T + 273.2}{T + 266.0}\right)^2 - \frac{0.21447\, P_V\, (T + 273.2)}{(T + 266.0)^2 (0.1833 - 1.665 \times 10^{-3} T)}$$; max. error = 1.51%

  (= 121.8 ; max. error = -4.65%)

---

*Assumed to be methane.

5. METHYL ALCOHOL [2,16,18,19,24], molecular weight = 32.043

Range of validity: -10° to 80° (2 kPa to 179 kPa)

- $\log_{10} P_V = 7.20585 - \dfrac{1582.27}{T + 239.73}$; max. error = -5.45% at -10° ; max. error = 0.32%, T > 15°

  $\left(= 7.3265 - \dfrac{2002.22}{T + 273.17}\right.$; max. error = 2.86%)

- $\rho_L = 0.8099 - 9.1979 \times 10^{-4} T$; max. error = 0.10%

  (same)

- $Z = 0.959 + 5.000 \times 10^{-4} T - 1.0833 \times 10^{-5} T^2$; max. error = = 0.13%)

  (= 1.0 ; max. error = 7.53%)

- $C_{PL} = 0.5660 + 1.622 \times 10^{-3} T$; max. error = -0.43%

  ($= 0.5260 + 3.200 \times 10^{-3} T$; max. error = 9.26%)

- $\overline{C_{PV}} = 0.3018 - 1.601 \times 10^{-3} T - 1.905 \times 10^{-6} T^2$; max. error = 3.00%

  ($C_{PV} = 0.2922 + 6.886 \times 10^{-4} T + 2.497 \times 10^{-7} T^2$; max. error = 100.72%)

- $\lambda = [216.56 + 1.129 \times 10^{-1} T - 2.446 \times 10^{-3} T^2] \left(\dfrac{T + 273.2}{T + 239.7}\right)^2$

  $- \dfrac{0.87037\, P_V\, (T + 273.2)}{(T + 239.7)^2 (0.8099 - 9.1979 \times 10^{-4} T)}$; max. error =-1.96%

  (= 262.8 ; max. error = -6.58%)

6. PROPANE [15,16,19,20,25], molecular weight = 58.12

Range of validity: -84° to 44° (1.5 kPa to 1520 kPa)

- $\log_{10} P_V = 5.9683 - \dfrac{818.56}{T + 248.68}$; max. error = -1.67% at 44° ; max. error = -0.73%, T < 27°

  (= $5.9545 - \dfrac{813.33}{T + 248.0}$; max. error = -1.20%, T < 27°)

- $\rho_L = 0.5301 - 1.425 \times 10^{-3} T - 2.788 \times 10^{-6} T^2$; max. error = 0.46%

  (= $0.5350 - 1.100 \times 10^{-3} T$; max. error = 5.65%)

- $Z = 0.8895 - 2.499 \times 10^{-3} T - 1.486 \times 10^{-5} T^2$; max. error = 0.85%

  (= 1.0 ; max. error = 33.3%)

- $C_{PL} = 0.5731 + 1.6913 \times 10^{-3} T + 1.705 \times 10^{-5} T^2$; max. error = -6.46%

  (= $0.6599 + 2.50 \times 10^{-3} T$; max. error = -15.41%)

- $\overline{C_{PV}} = 0.2373 - 1.6045 \times 10^{-3} T - 1.4184 \times 10^{-5} T^2$;
  max. error = -21.28% at -70°
  max. error = 2.52%, T > -70°

  ($C_{PV} = 0.3700 + 1.158 \times 10^{-3} T - 4.083 \times 10^{-7} T^2$; max. error = 154.32%)

- $$\lambda = [75.512 - 2.121 \times 10^{-1} T - 1.2615 \times 10^{-3} T^2] \left(\frac{T + 273.2}{T + 248.7}\right)^2 - \frac{0.45026\, P_V\, (T + 273.2)}{(T + 248.7)^2 (0.5301 - 1.10 \times 10^{-3} T)}$$; max. error = 2.55%

  (= 101.78 ; max. error = 46.72%)

AD-A095 413 SOUTHWEST RESEARCH INST SAN ANTONIO TEX F/G 13/10
EXPERIMENTAL VERIFICATION AND REVISION OF THE VENTING RATE MODE--ETC(U)
NOV 80 F T DODGE, E B BOWLES, J E MANN DOT-CG-73623-A
UNCLASSIFIED SWRI-02-5295 USCG-D-63-80 NL

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A095 413

APPENDIX C. COMPUTER PROGRAM

The analytical model presented in Section II has been programmed for numerical solution in the computer code TVENT, which is outlined in this appendix. The basic technique used in the code is to assume that a small percentage of the cargo mass is discharged and then compute the time increment for the discharge to occur, using the various energy and mass balances and flow relations. After the model has been "solved" to a prescribed degree of accuracy for this incremental discharge, an additional discharge is assumed, and the solution process repeated. This continues until tank conditions are computed that make further discharges impossible.

TVENT is arranged into a "MAIN" code and a number of subroutines that generally correspond to the various submodels comprising the entire venting rate model. Flow charts giving the logic for the MAIN program and the subroutines are given in Figures C.1 through C.12 and Tables C.2, C.3, and C.4. Table C.1 gives the required inputs for the program in its present form.

To describe the code briefly, the MAIN program: (1) organizes the input data; (2) determines whether the cargo is volatile; (3) determines whether liquid or vapor or both are discharged; (4) selects the increment of mass to be discharged; (5) determines whether the calculations for any one iteration have converged; (6) determines when the discharge is completed; and (7) calls the various subroutines that perform the detailed computations. Before each calculation cycle, MAIN also calls the subroutine INGEST, which determines whether the tank conditions are appropriate for air or water ingestion. A test for choked flow conditions (CHOKTEST) is called before the first cycle and each cycle thereafter so long as choked outflow can occur.

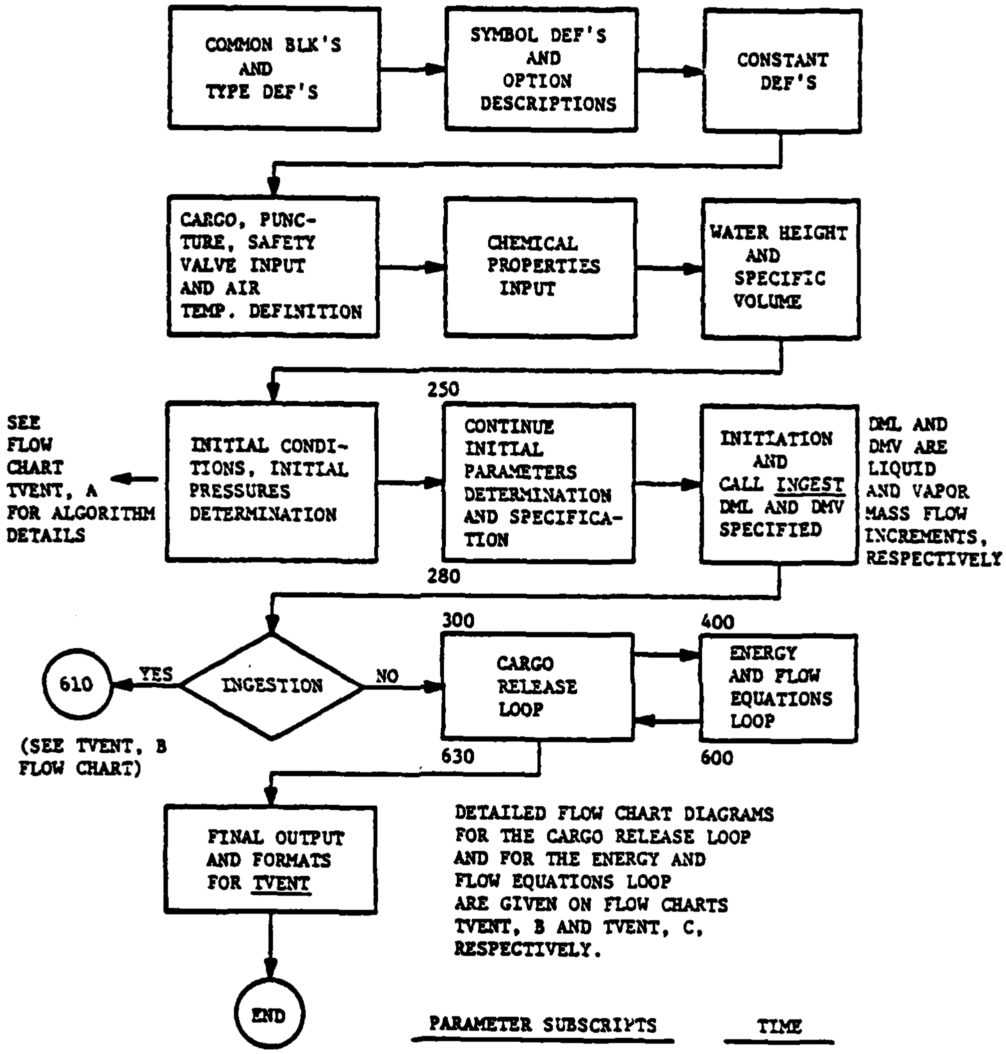
Subroutines are used to make most of the calculations. ENERGY solves the energy and mass balances for a volatile cargo and calls FLOW1 to compute discharge flow rates. NONENER and FLOW2 are used similarly for nonvolatile cargos. INGEST performs all the logic operations needed to determine whether air or water ingestion can occur at any instant. AIRIN computes the change in tank conditions when air bubbles are ingested by calling ENERGY2 (for volatile cargos) or NONENER2 (for nonvolatile cargos) to determine the vapor space pressure rise; a return to ENERGY or NONENER is then made to compute the subsequent liquid discharge. WATIN computes the cargo discharge and water inflow when water is ingested, and calls FLOW2 to compute the outflow. NOOUT is used to compute the discharge when water can be ingested at the instant the puncture is opened, as well as for certain other water ingestion cases similar to this. Other self-explanatory subroutines compute cargo properties and miscellaneous data.

A computer listing of each routine is also given in this appendix. Table C.5 explains the correspondence between the symbols used in the analysis and those used in the computer code. Table C.6 gives the formats to be used to enter the input data in TVENT.

Other notes on the use of the computer code include:

1. The normal outputs are the total mass of cargo liquid, cargo vapor, and air released, and the total discharge time.
2. The code assumes that only liquid or only vapor can be discharged through circular or horizontal slot-like punctures; when the liquid surface intersects this type of puncture, only liquid is discharged until the level drops b low the puncture. Simultaneous liquid and vapor discharges are allowed for vertical slot-like punctu es when the liquid level intersects the puncture

3. Similarly, circular or horizontal slot-like punctures must be either completely open to the air or completely submerged. Only for a vertical slot-like puncture is the water level allowed to intersect the puncture.
4. The code assumes the cross-sectional area of the tank is constant; for spherical or other tank shapes, an effective tank height should be input such that V_T/Z_T gives a representative or average area.
5. For nonvolatile substances, only the liquid density correlation must be input accurately. The other correlations, if they are not known for that cargo, can be input as any convenient values (say, one). Care should be taken, however, to make sure that the fictitious vapor pressure correlation predicts positive pressures that are significantly less than atmospheric.



PARAMETER SUBSCRIPTS	TIME
1	t_{i-1}
2	t_i
3, 4	$t_i + \delta t$ or t_{i+1}

FIGURE C-1. PROGRAM TVENT (MAIN PROGRAM) FLOW CHART

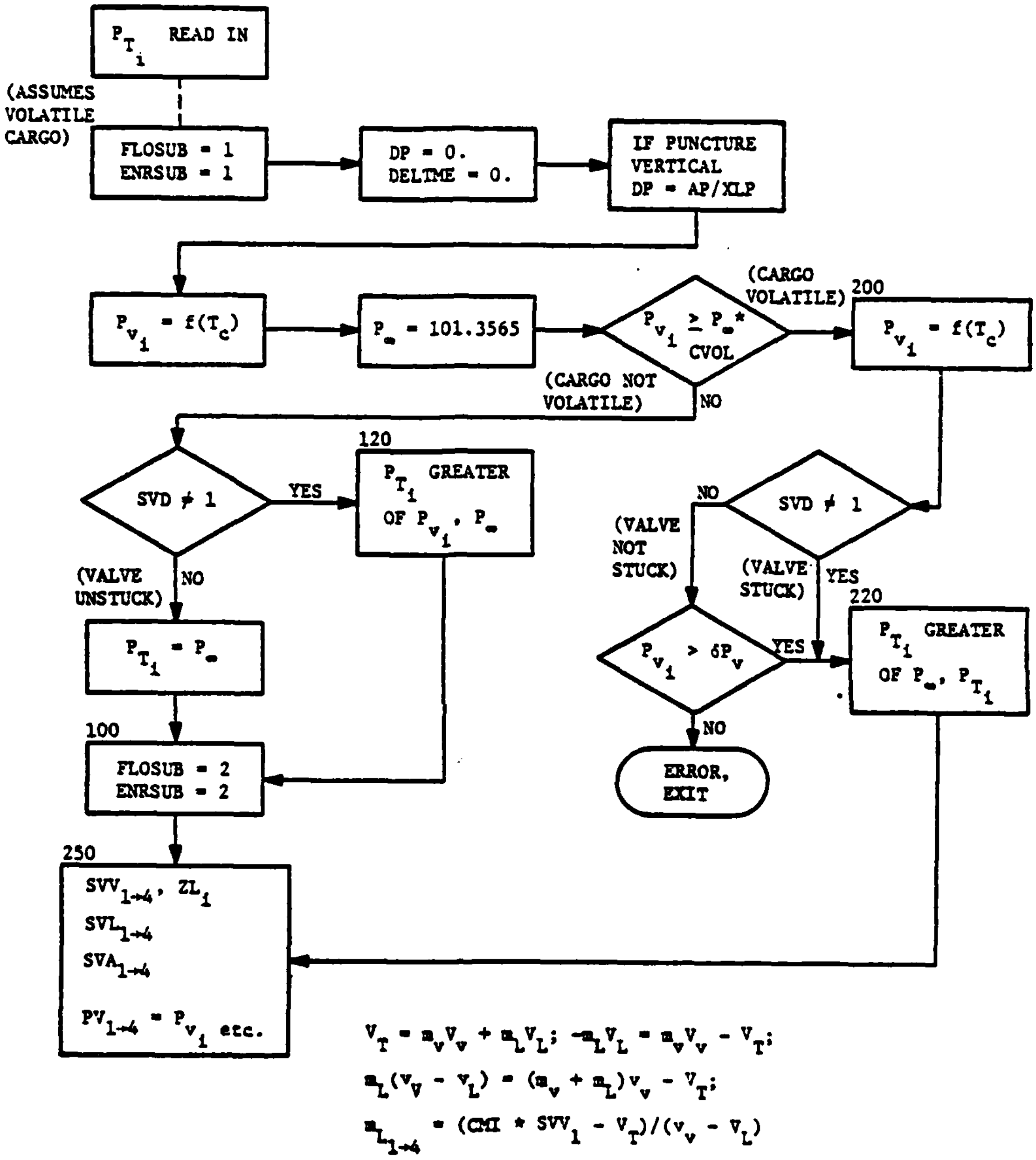


FIGURE C-1. PROGRAM TVENT (MAIN PROGRAM) FLOW CHART (Cont'd)
(TVENT, A - Initial Conditions, Initial Pressures Determinations Algorithm Flow Chart)

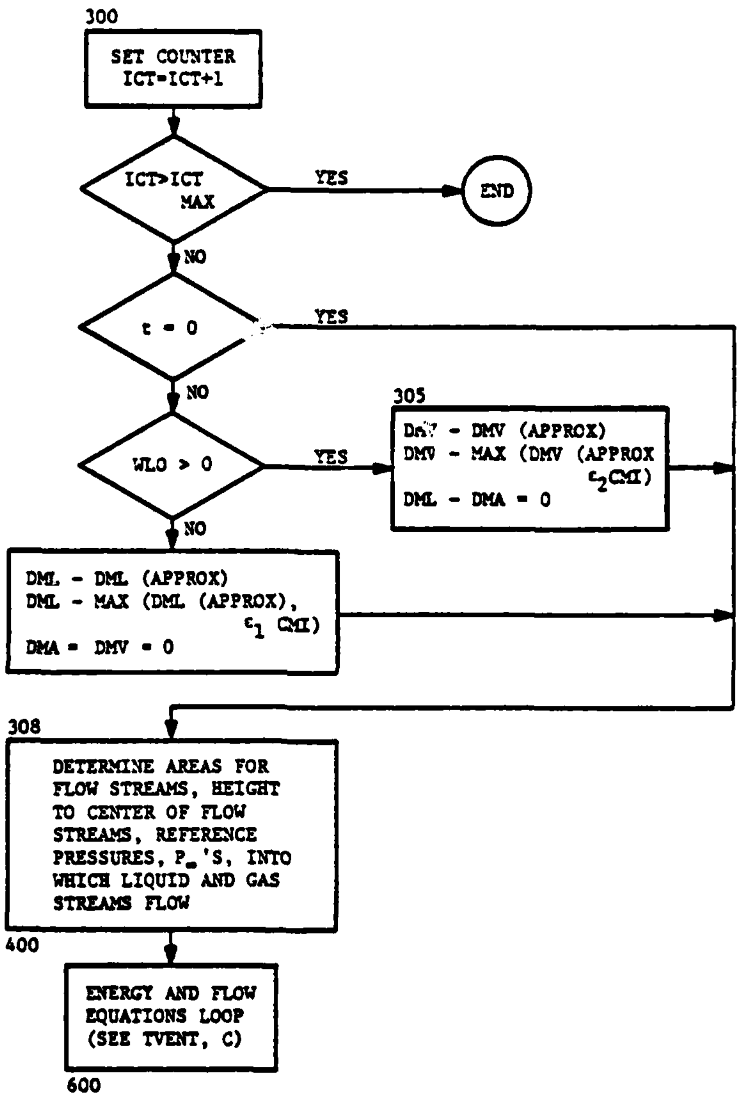


FIGURE C-1. PROGRAM TVENT (MAIN PROGRAM) FLOW CHART (Cont'd)
(TVENT, B - Cargo Release Loop Flow Chart)

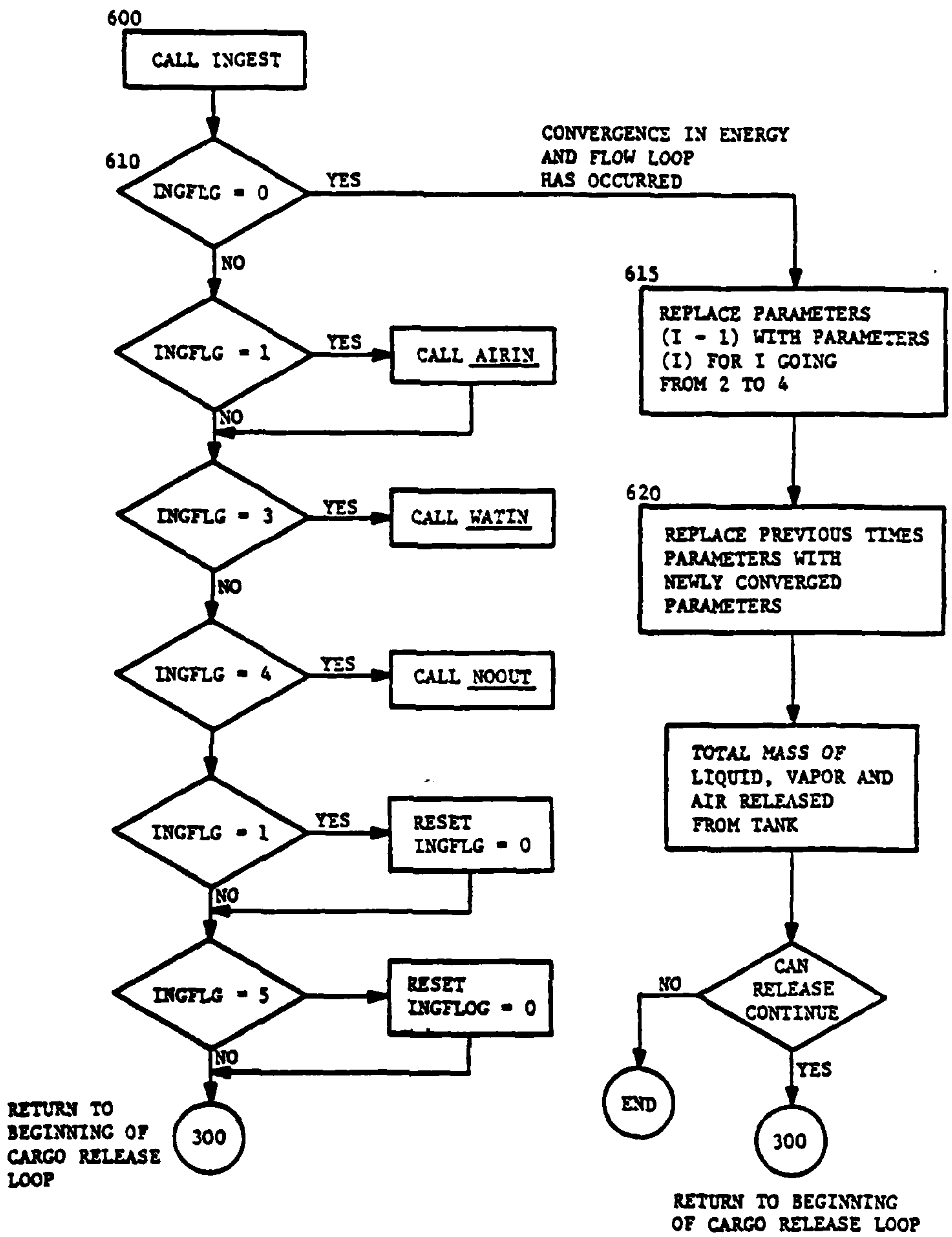


FIGURE C-1. PROGRAM TVENT (MAIN PROGRAM) FLOW CHART (Cont'd)
(TVENT, B - Cargo Release Loop Flow Chart)

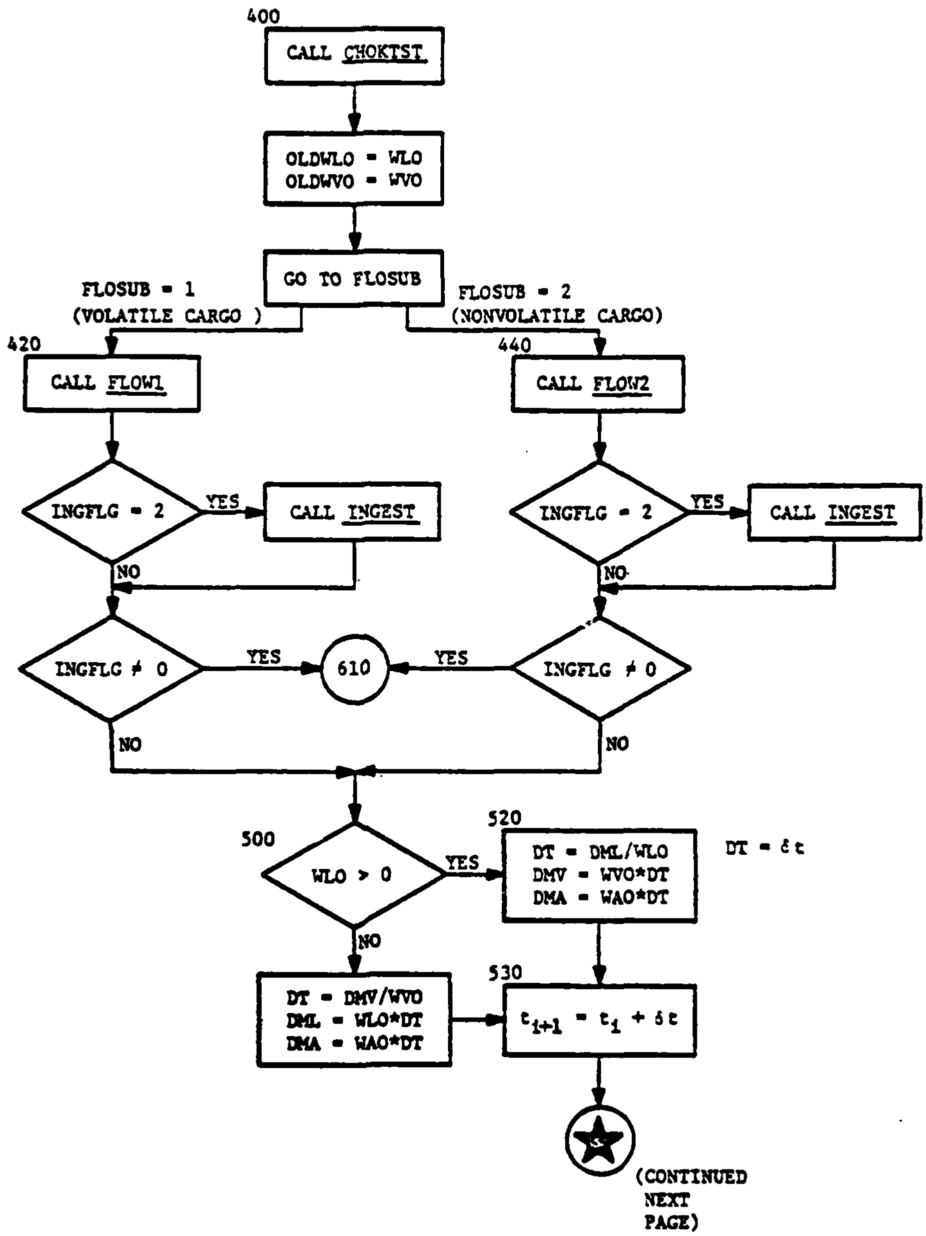


FIGURE C-1. PROGRAM TVENT (MAIN PROGRAM) FLOW CHART (Cont'd)
(TVENT, C - Energy and Flow Equations Loop Flow Chart)

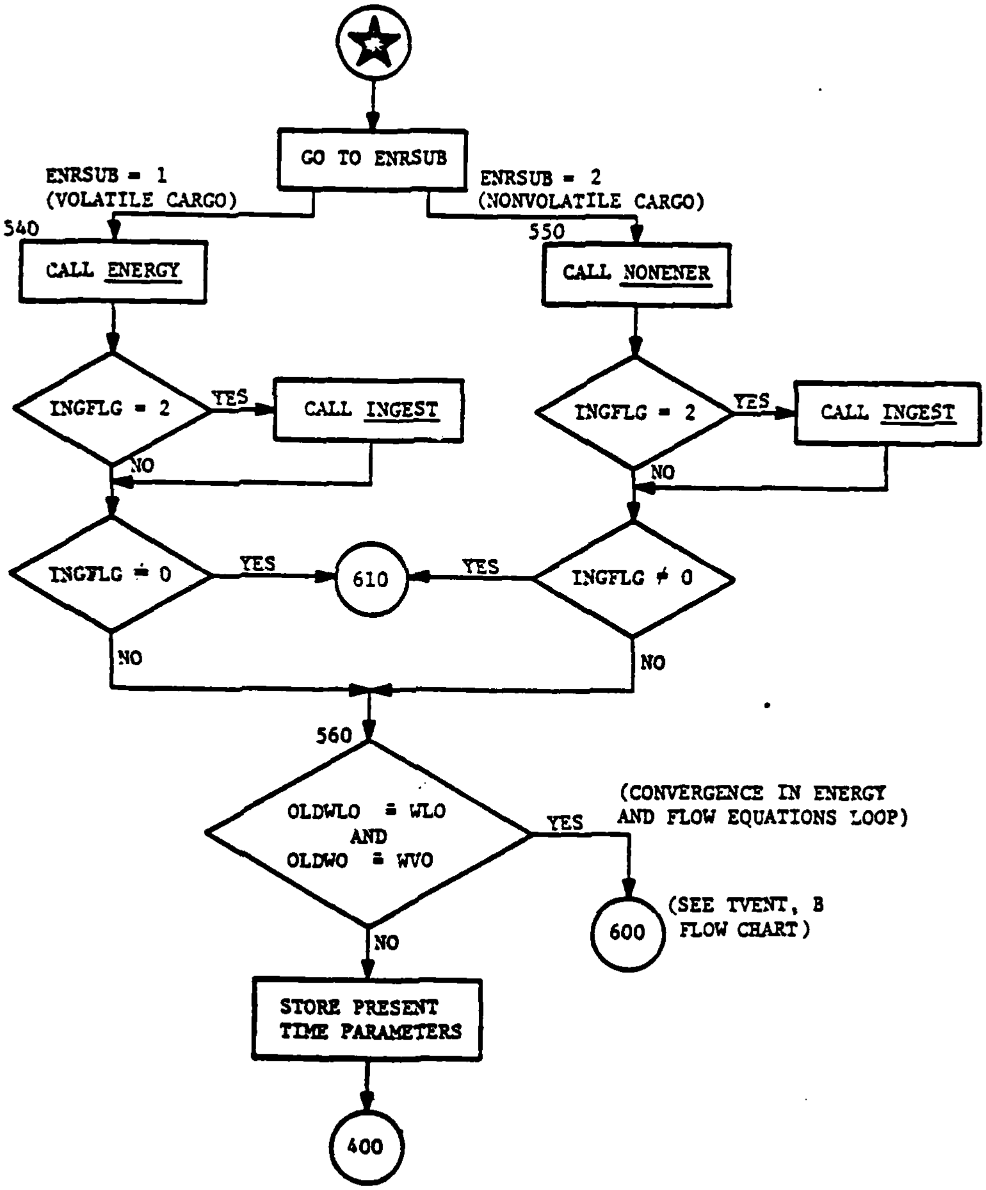


FIGURE C-1. PROGRAM TVENT (MAIN PROGRAM) FLOW CHART (Concl'd)
(TVENT, C - Energy and Flow Equations Loop Flow Chart)

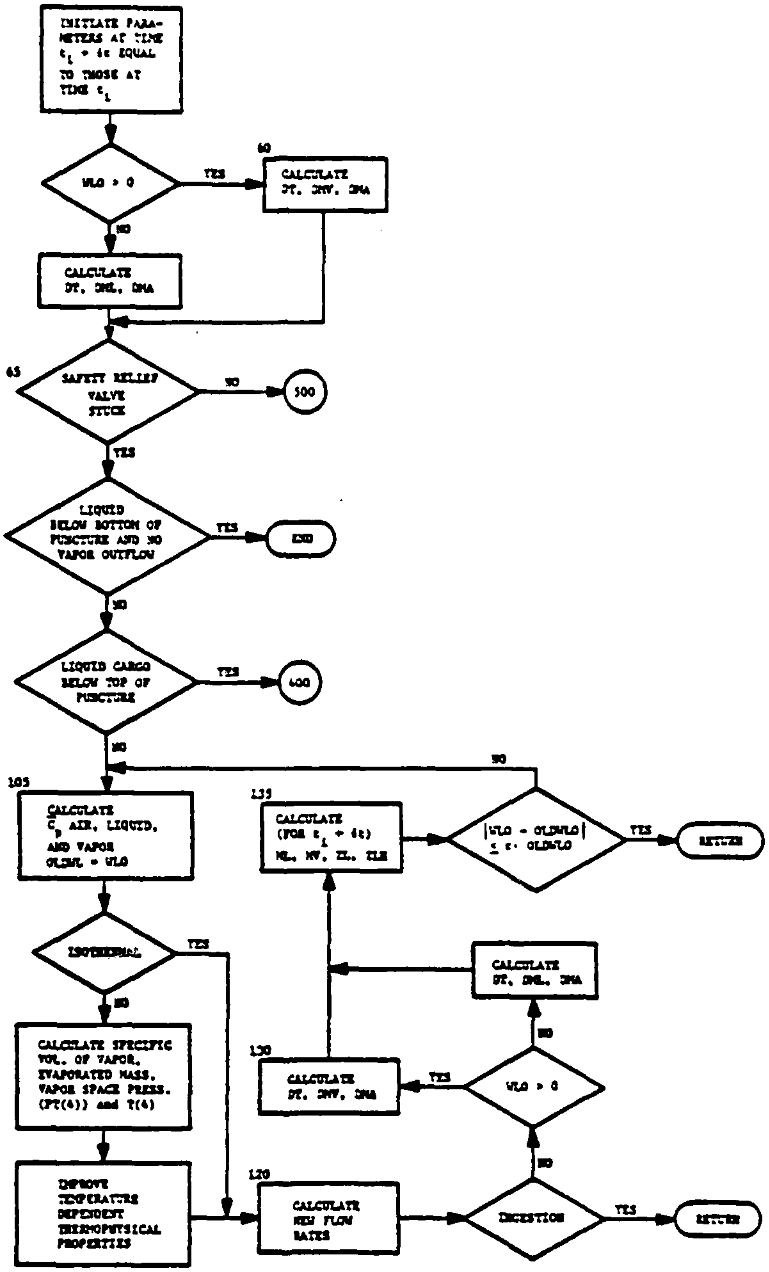


FIGURE C-2. ENERGY SUBROUTINE FLOW CHART

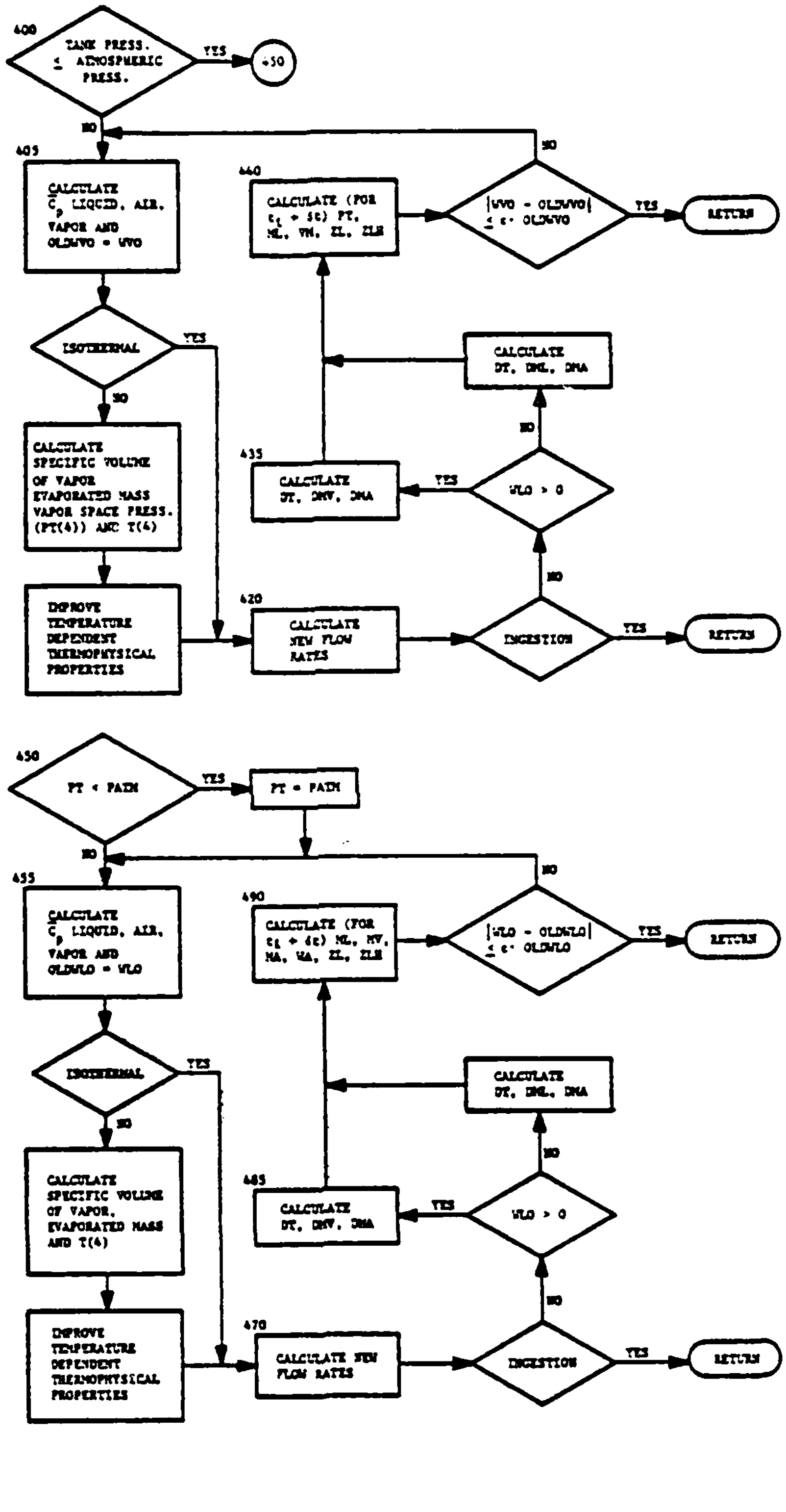


FIGURE C-2. ENERGY SUBROUTINE FLOW CHART (Cont'd)

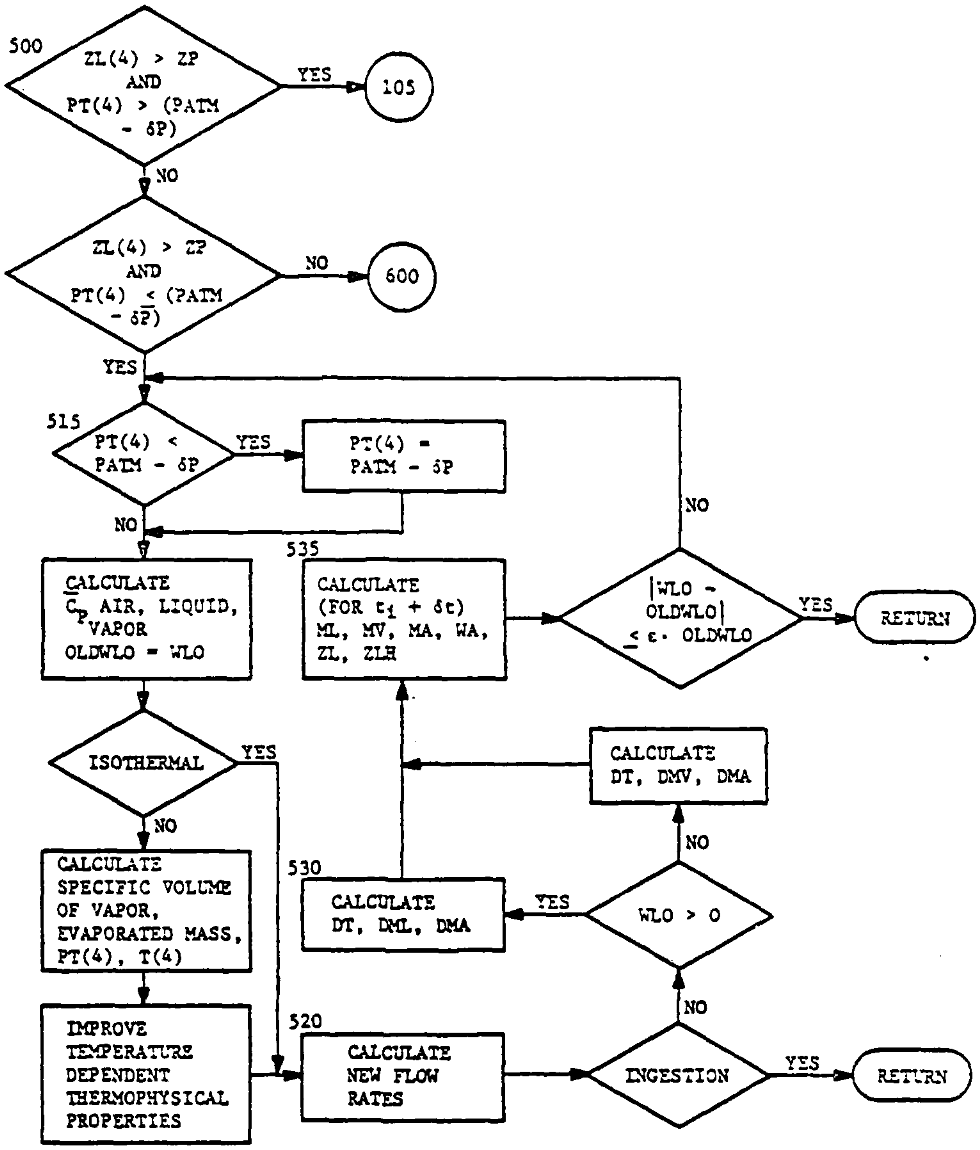


FIGURE C-2. ENERGY SUBROUTINE FLOW CHART (Cont'd)

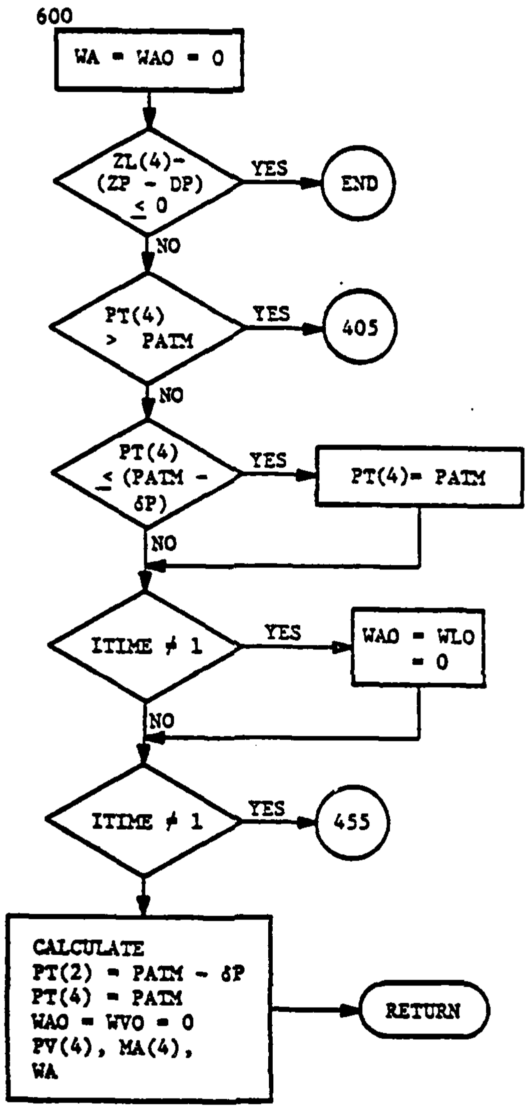


FIGURE C-2. ENERGY SUBROUTINE FLOW CHART (Concl'd)

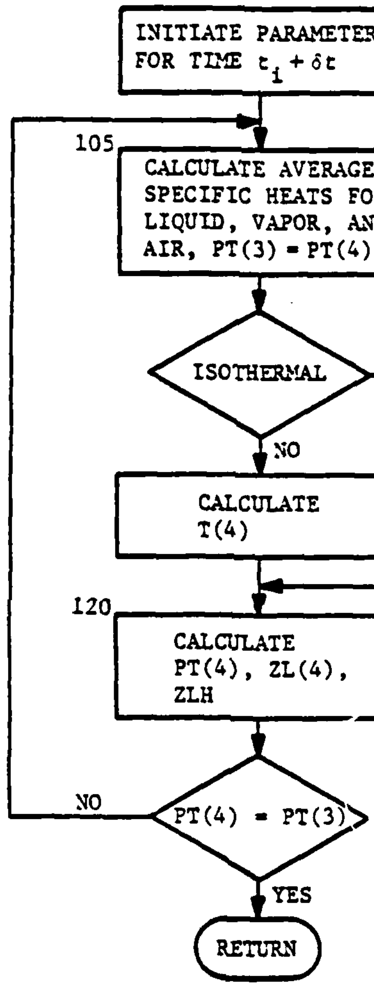
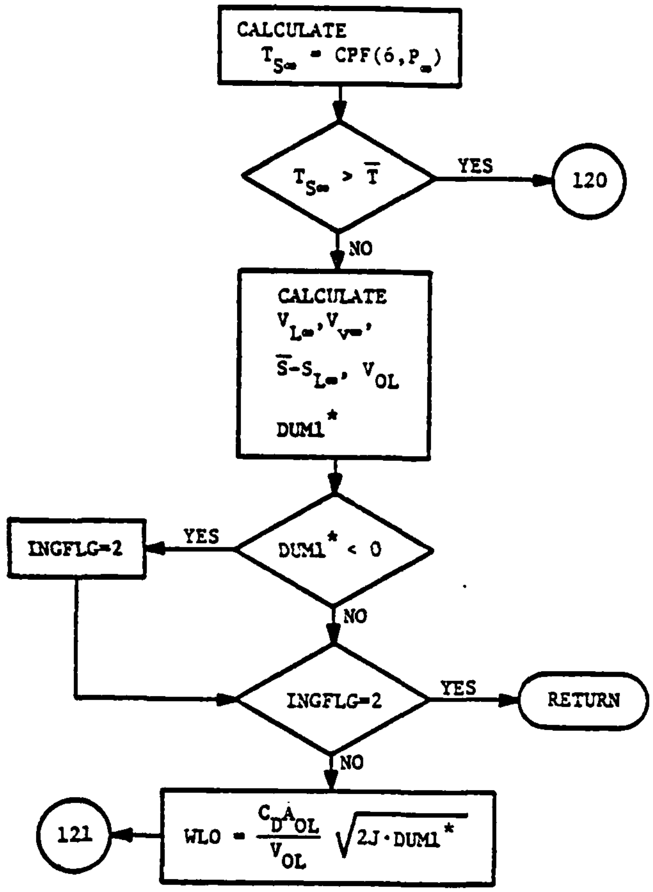


FIGURE C-3. SUBROUTINE ENERGY2 (KOUNT) FLOW CHART



*DUM1 = $\bar{C}_{pL}(\bar{T} - T_{S\infty}) - T_{S\infty}(\bar{S} - S_{L\infty}) + 10^4(\bar{P}_T - \bar{P}_v)\bar{V}_L/J + g(\bar{Z}_L - \bar{Z}_{Lh})/J$

**DUM2 = $2(10^4(\bar{P}_T - P_\infty)\bar{V}_L + g(\bar{Z}_L - \bar{Z}_{Lh}))$

FIGURE C-4. SUBROUTINE FLOW1 FLOW CHART

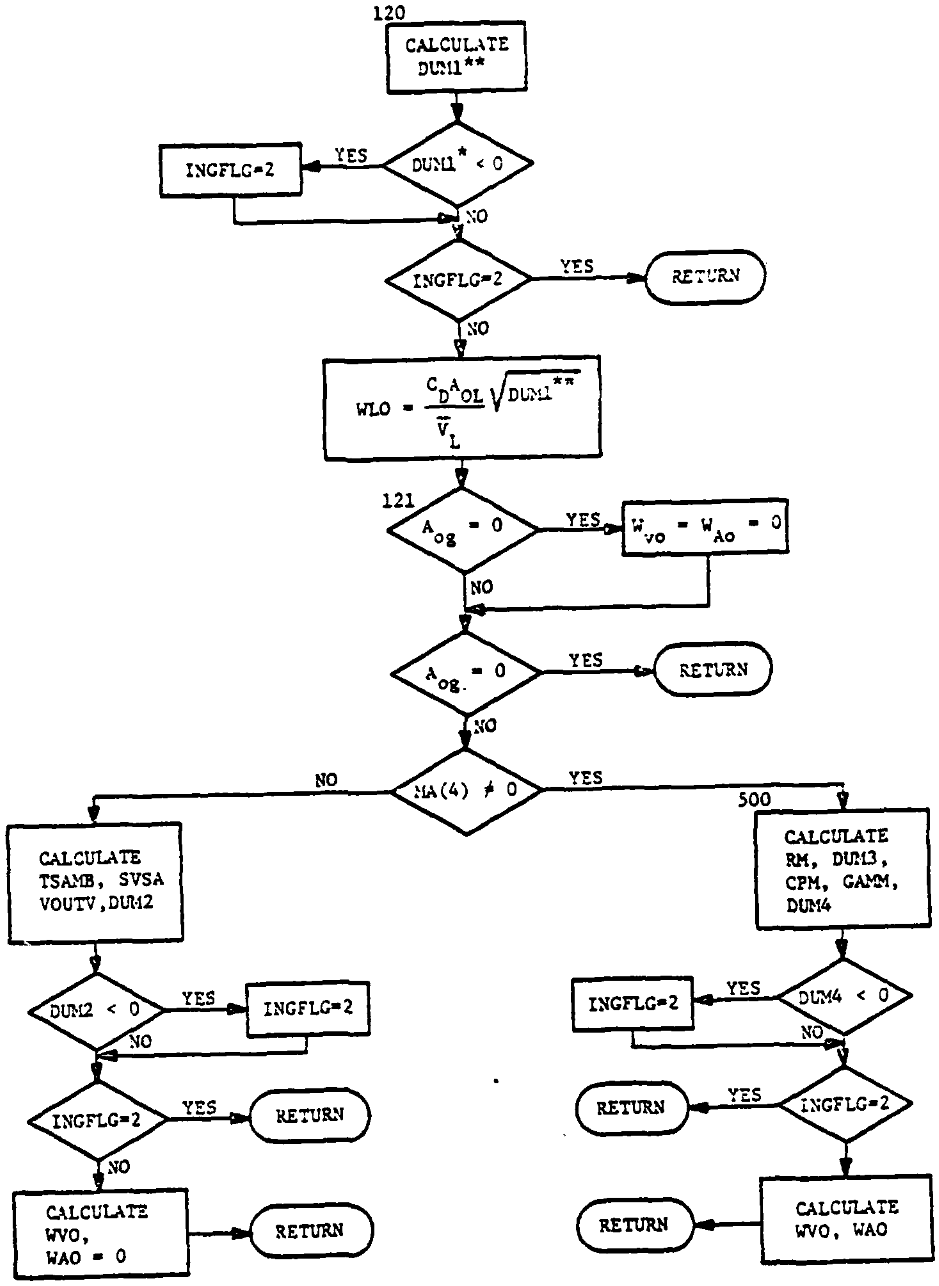


FIGURE C-4. SUBROUTINE FLOW1 FLOW CHART (Concl'd)

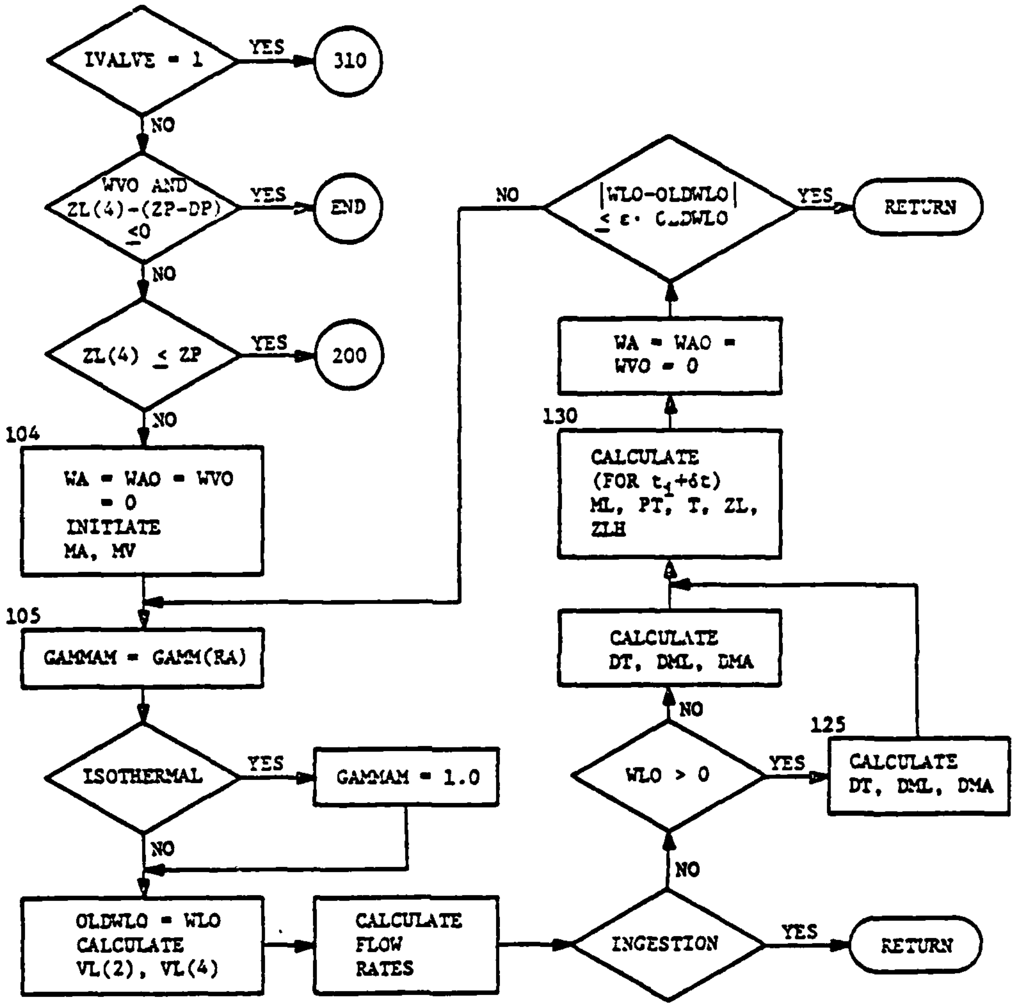


FIGURE C-5. SUBROUTINE NONENER FLOW CHART

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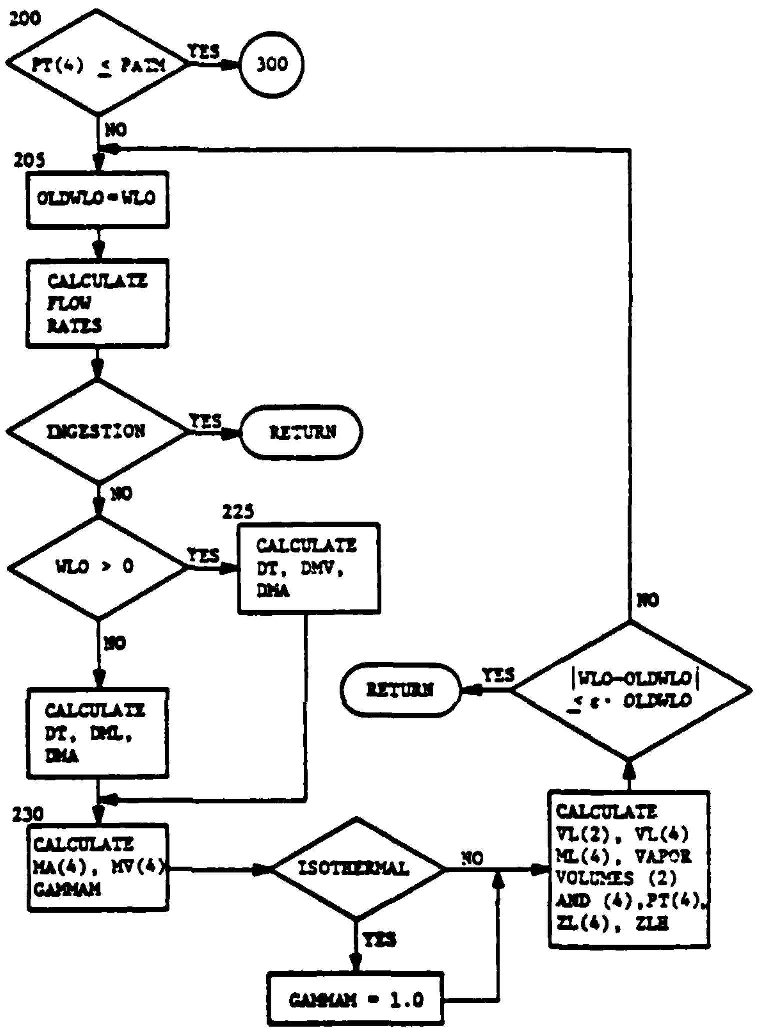


FIGURE C-5. SUBROUTINE NONENER FLOW CHART (Cont'd)

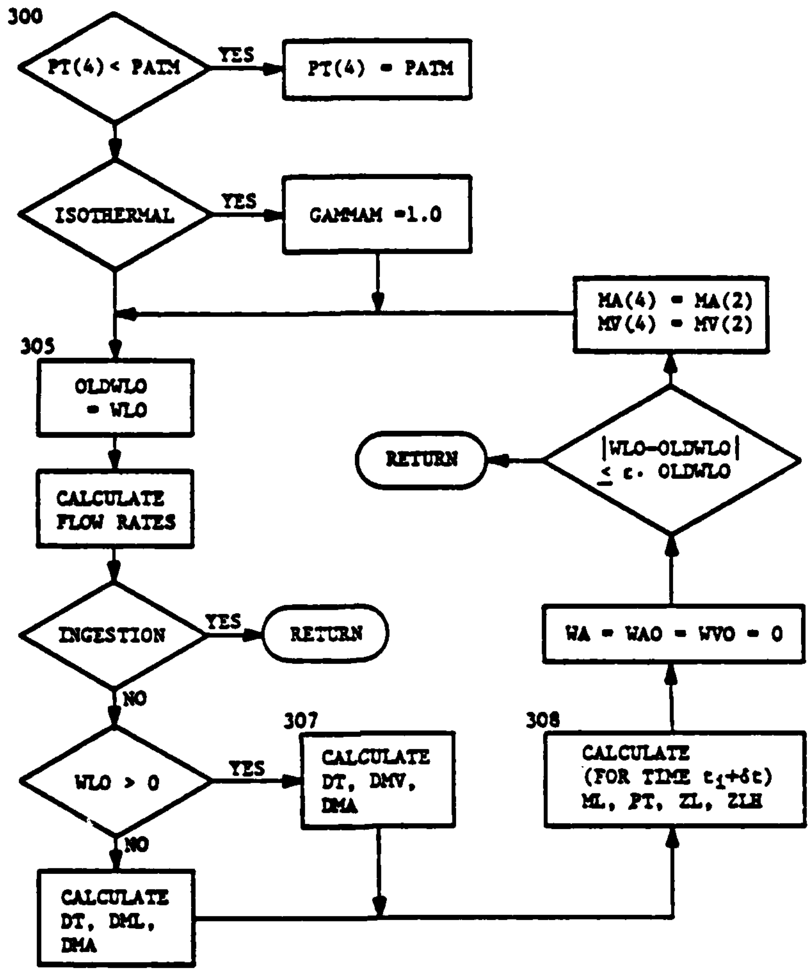


FIGURE C-5. SUBROUTINE NONENER FLOW CHART (Cont'd)

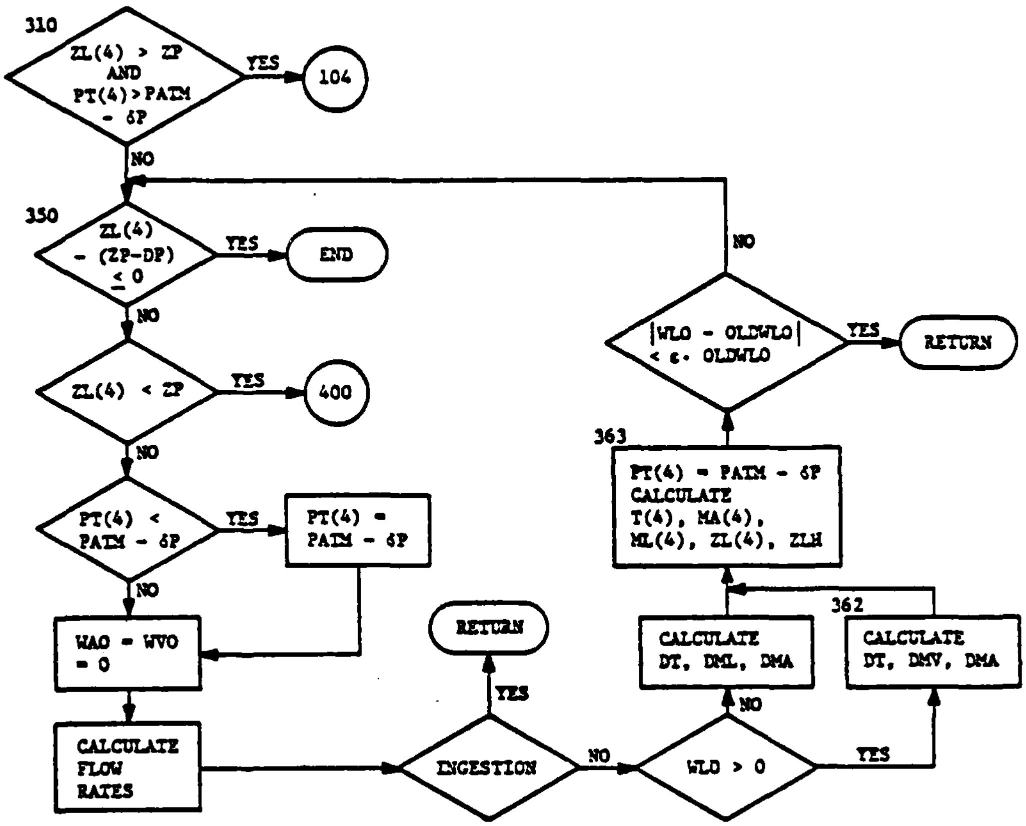


FIGURE C-5. SUBROUTINE NONENER FLOW CHART (Cont'd)

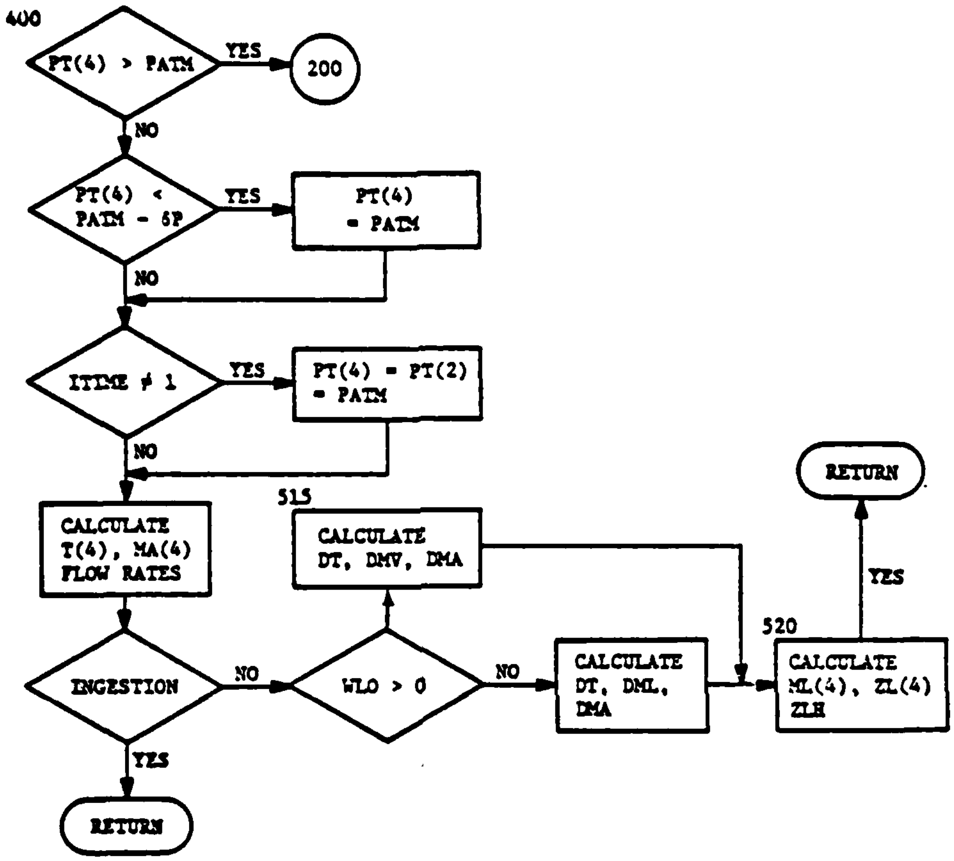


FIGURE C-5. SUBROUTINE NONENER FLOW CHART (Concl'd)

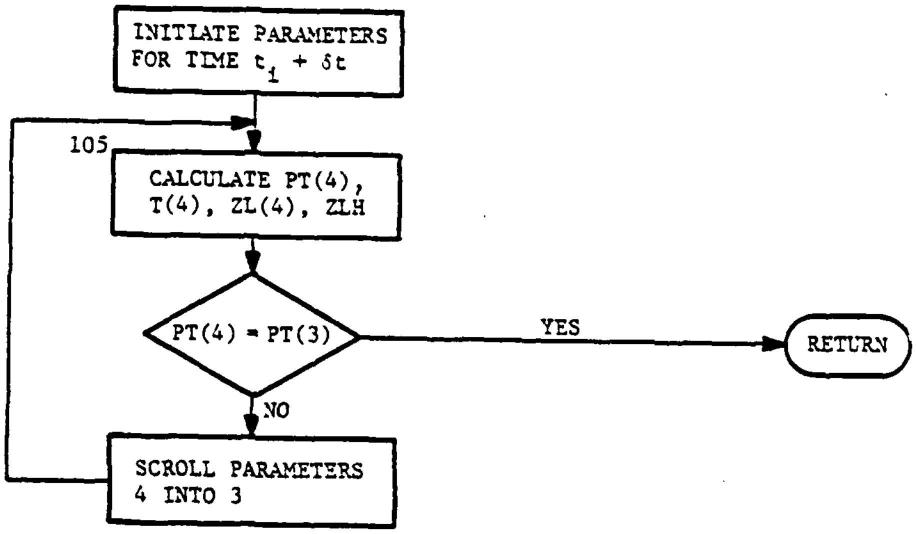
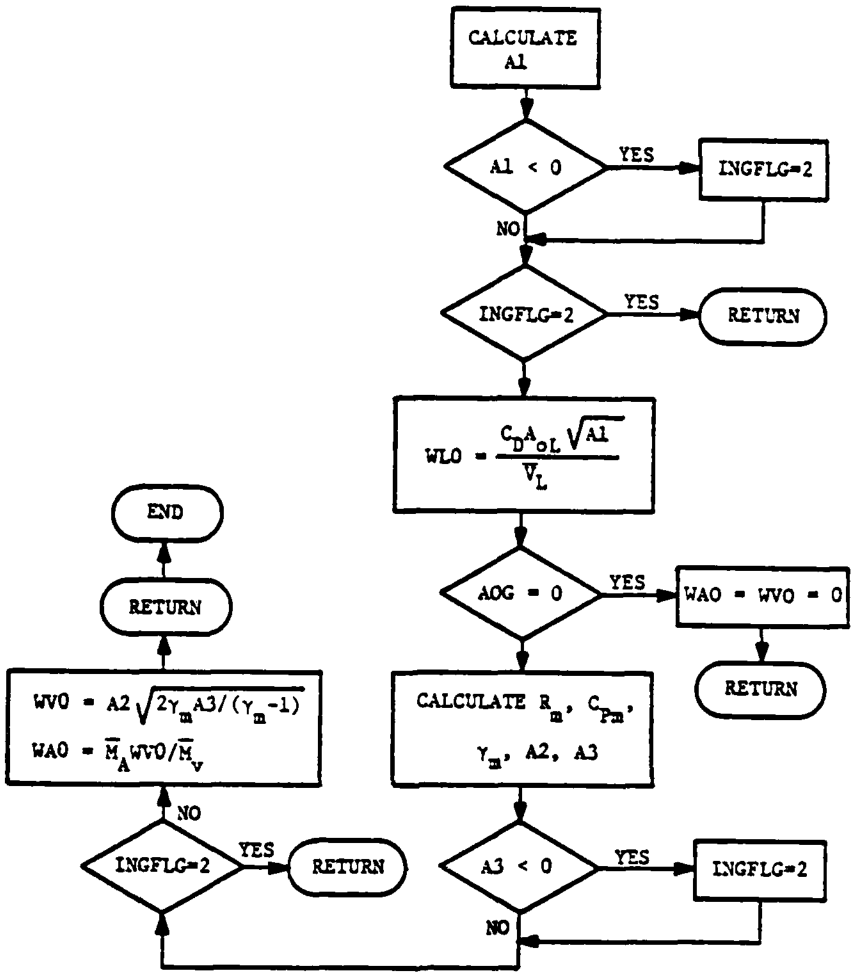


FIGURE C-6. SUBROUTINE NONENG2 (KOUNT)
FLOW CHART



$$A1 = 2(10^4(\overline{P}_T - P_\infty)\overline{V}_L + g\,(\overline{Z}_L - \overline{Z}_{Lh}))$$

$$A2 = 10^2\overline{M}_v C_D A_{OG}\overline{P}_T/((\overline{M}_v + \overline{M}_A)\sqrt{R_m\overline{T}}\,)$$

$$A3 = (P_\infty \cdot g/\overline{P}_T)^{2/\gamma m} - (P_\infty \cdot g/\overline{P}_T)^{(\gamma m + 1)/\gamma m}$$

FIGURE C-7. SUBROUTINE FLOW2 FLOW CHART

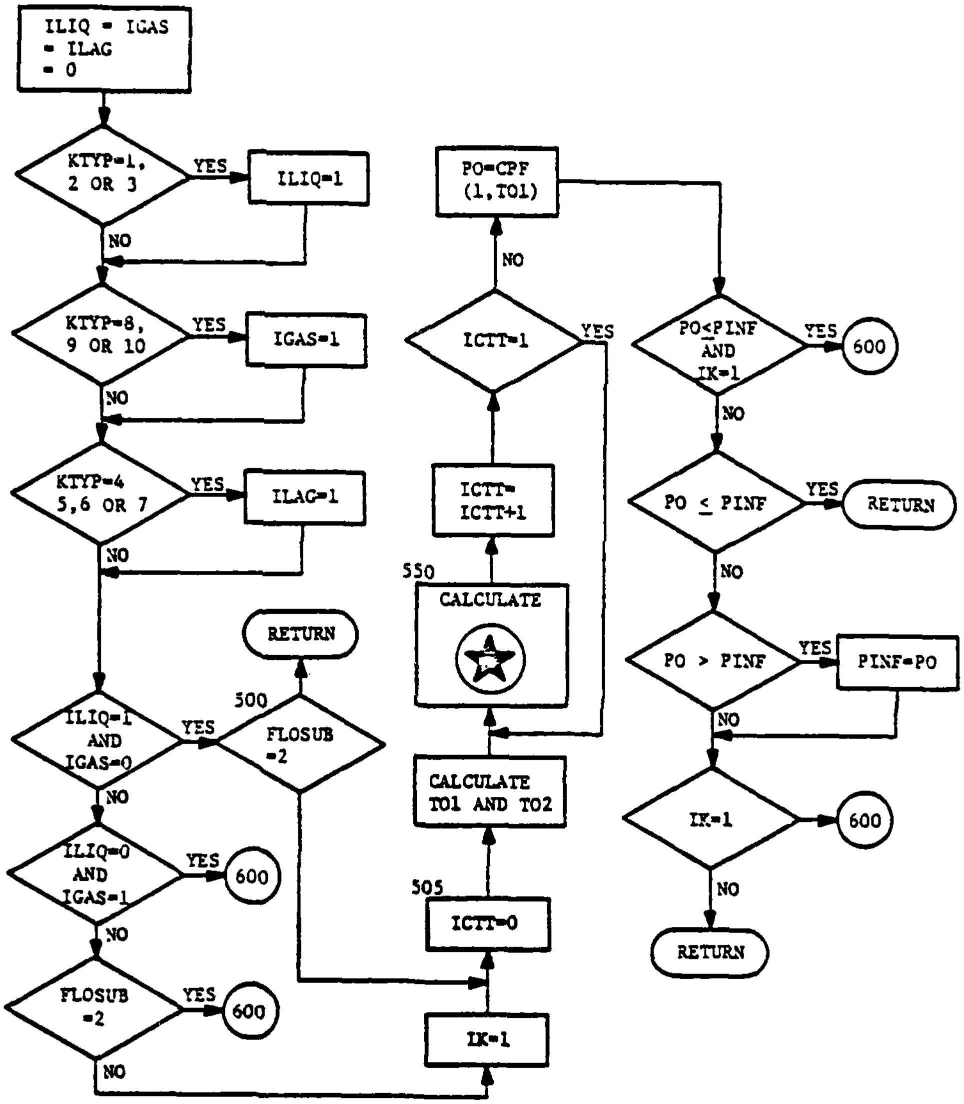
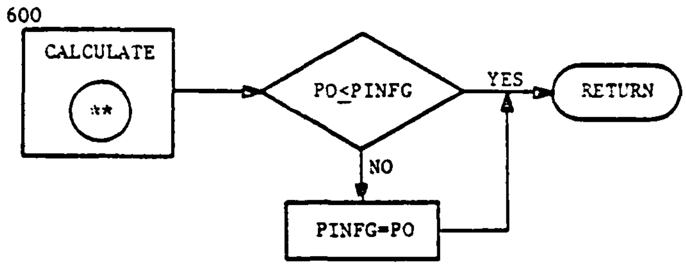


FIGURE C-8. SUBROUTINE CHOKTST (KTYP) FLOW CHART



**

RVI
GAMMAM (a)
PO (a)
TO
GPVAVE
GAMMAM (b)
PO (b)

*

CPLT01
CPLT02
SVV (4)
LAM01
LAM02
X01
X02
P01
P02
VV01
VV02

VL01
VL02
LAMBAR
DERIV1
DERIV2
DELT
T01
T02

FIGURE C-8. SUBROUTINE CHOKTST (KTYP) FLOW CHART
(Concl'd)

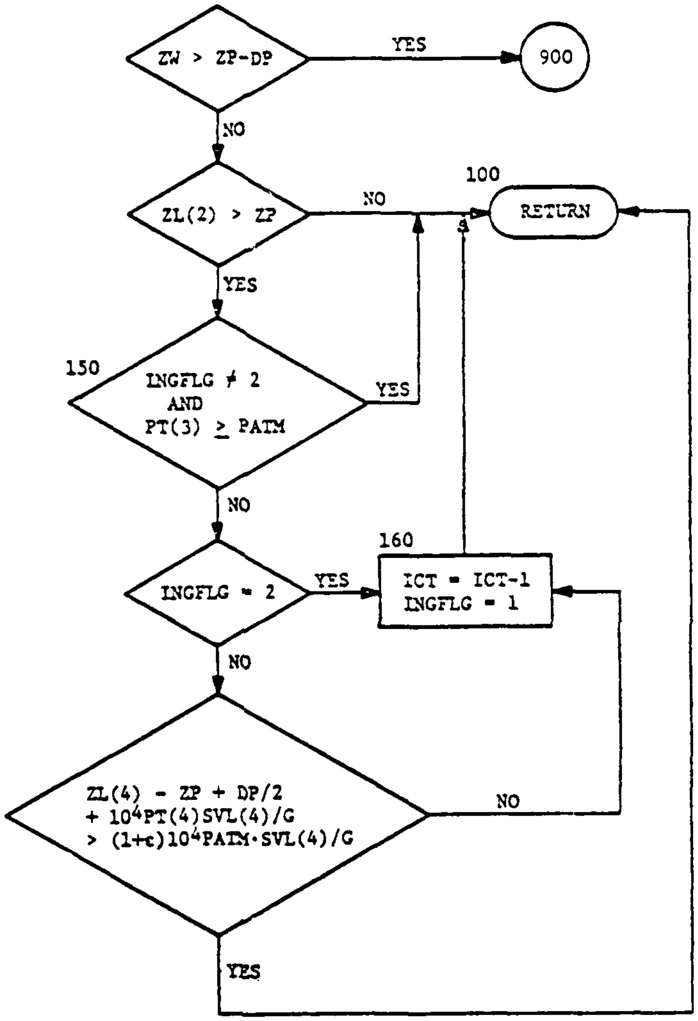


FIGURE C-9. SUBROUTINE INGEST FLOW CHART

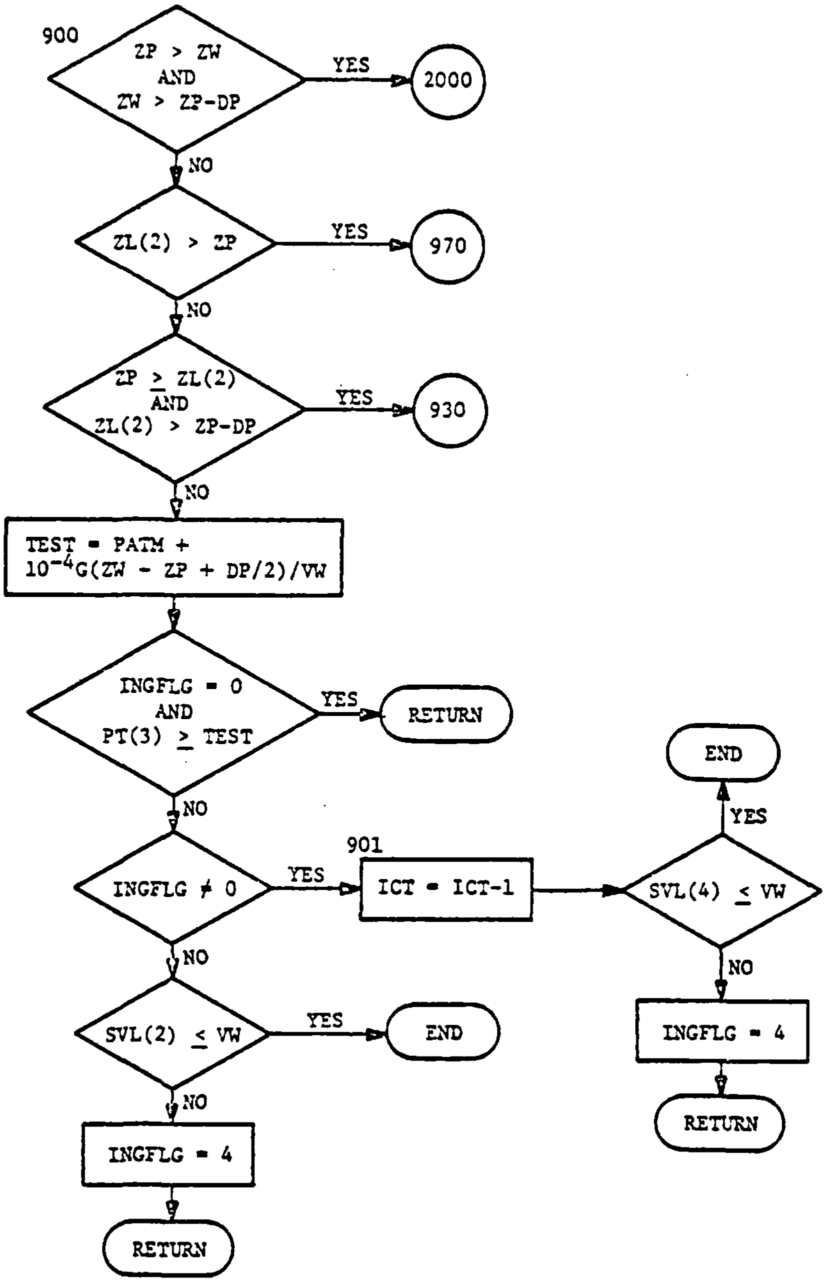


FIGURE C-9. SUBROUTINE INGEST FLOW CHART (Cont'd)

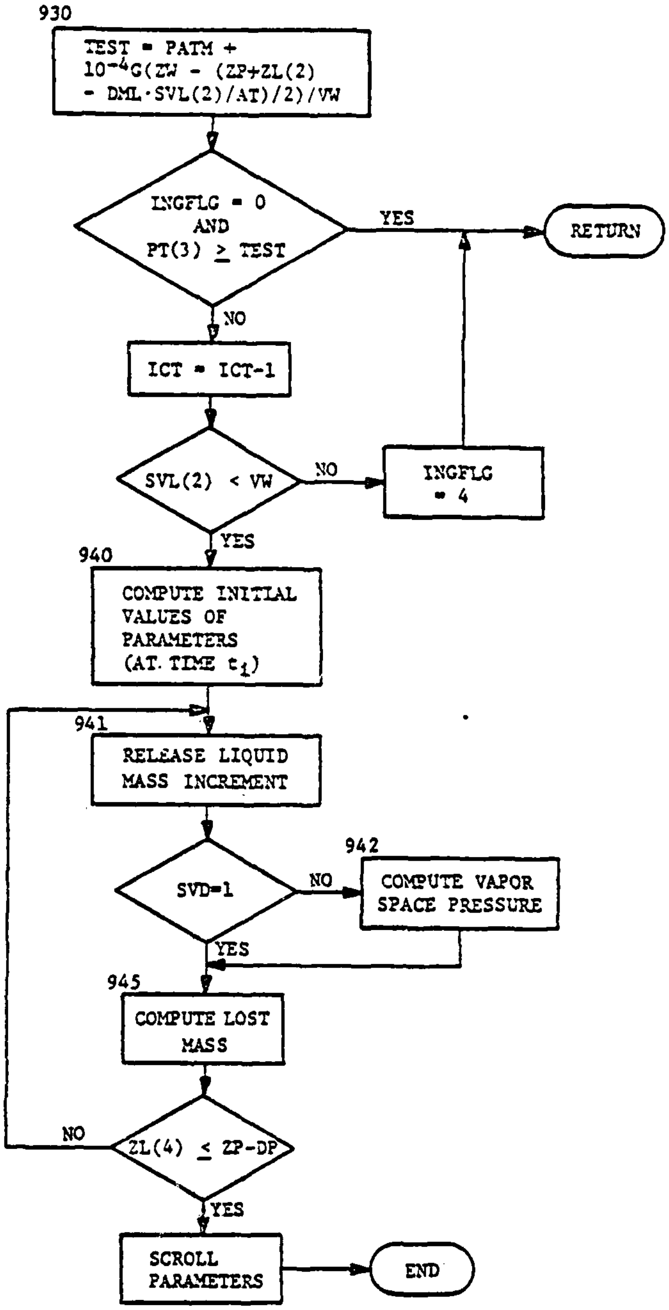


FIGURE C-9. SUBROUTINE INGEST FLOW CHART (Cont'd)

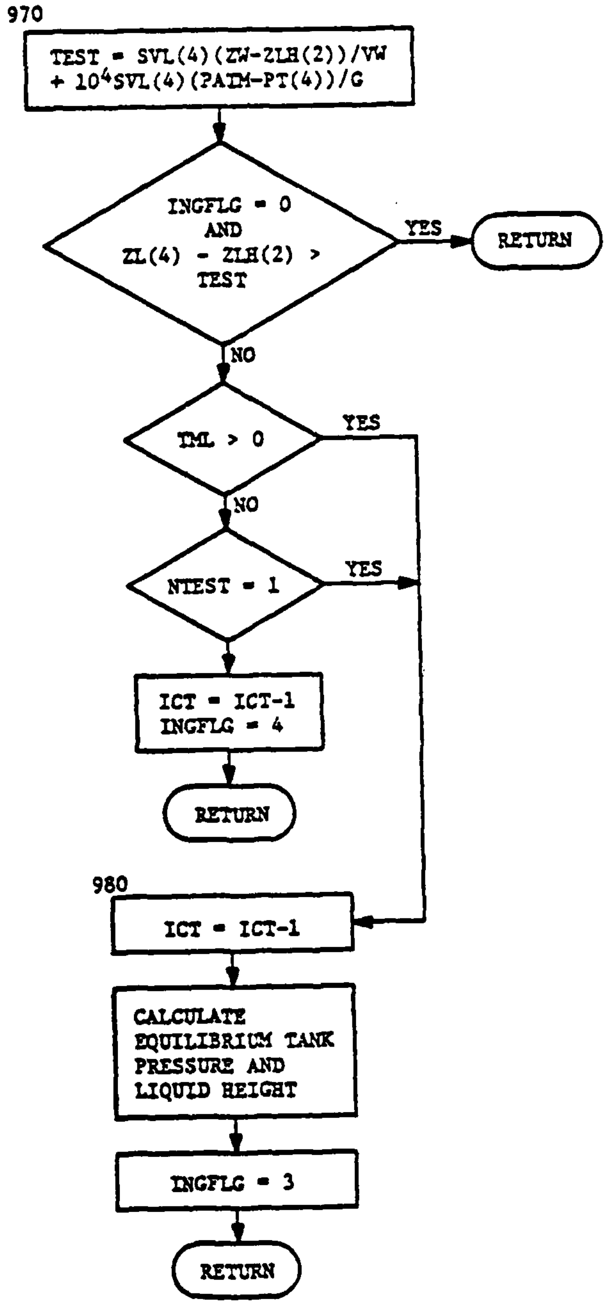


FIGURE C-9. SUBROUTINE INGEST FLOW CHART (Cont'd)

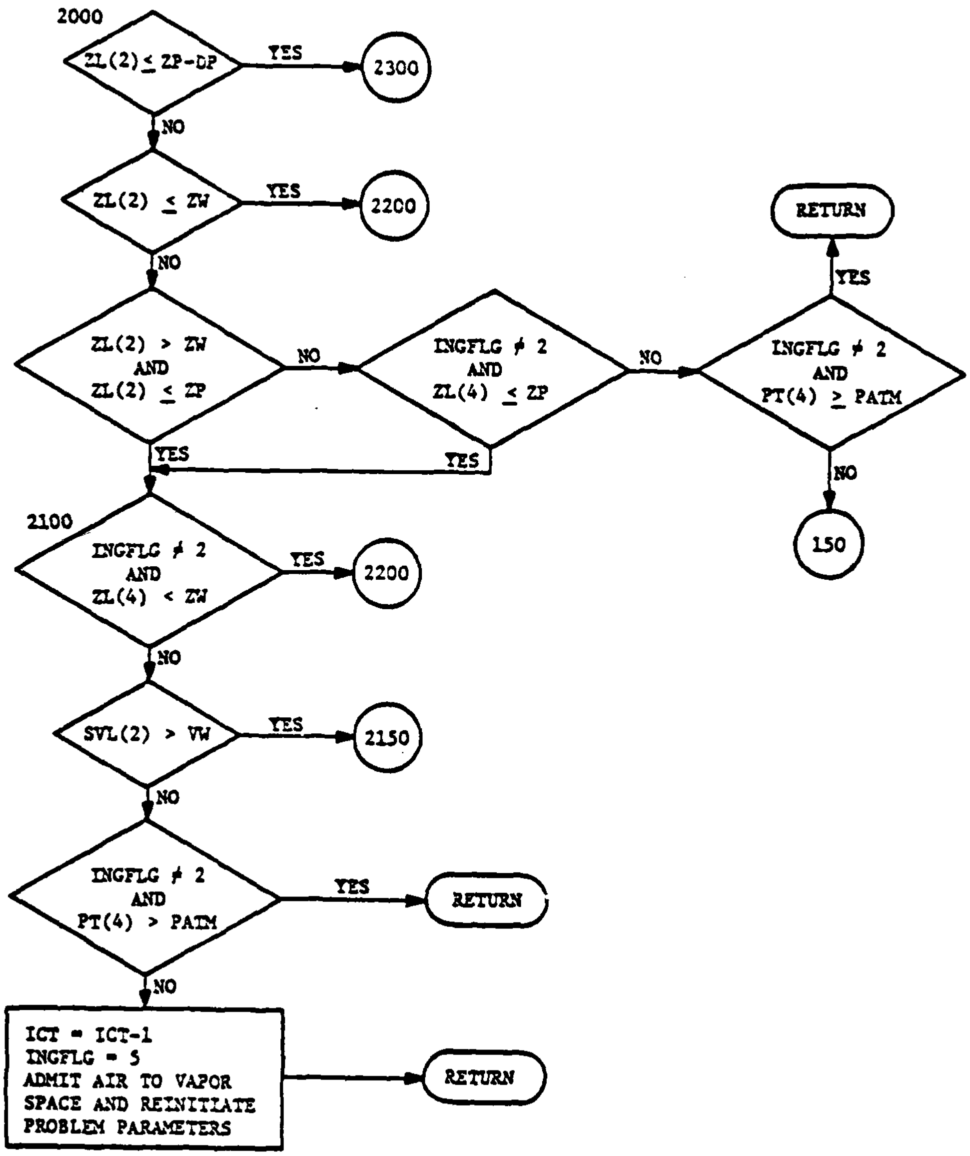


FIGURE C-9. SUBROUTINE INGEST FLOW CHART (Cont'd)

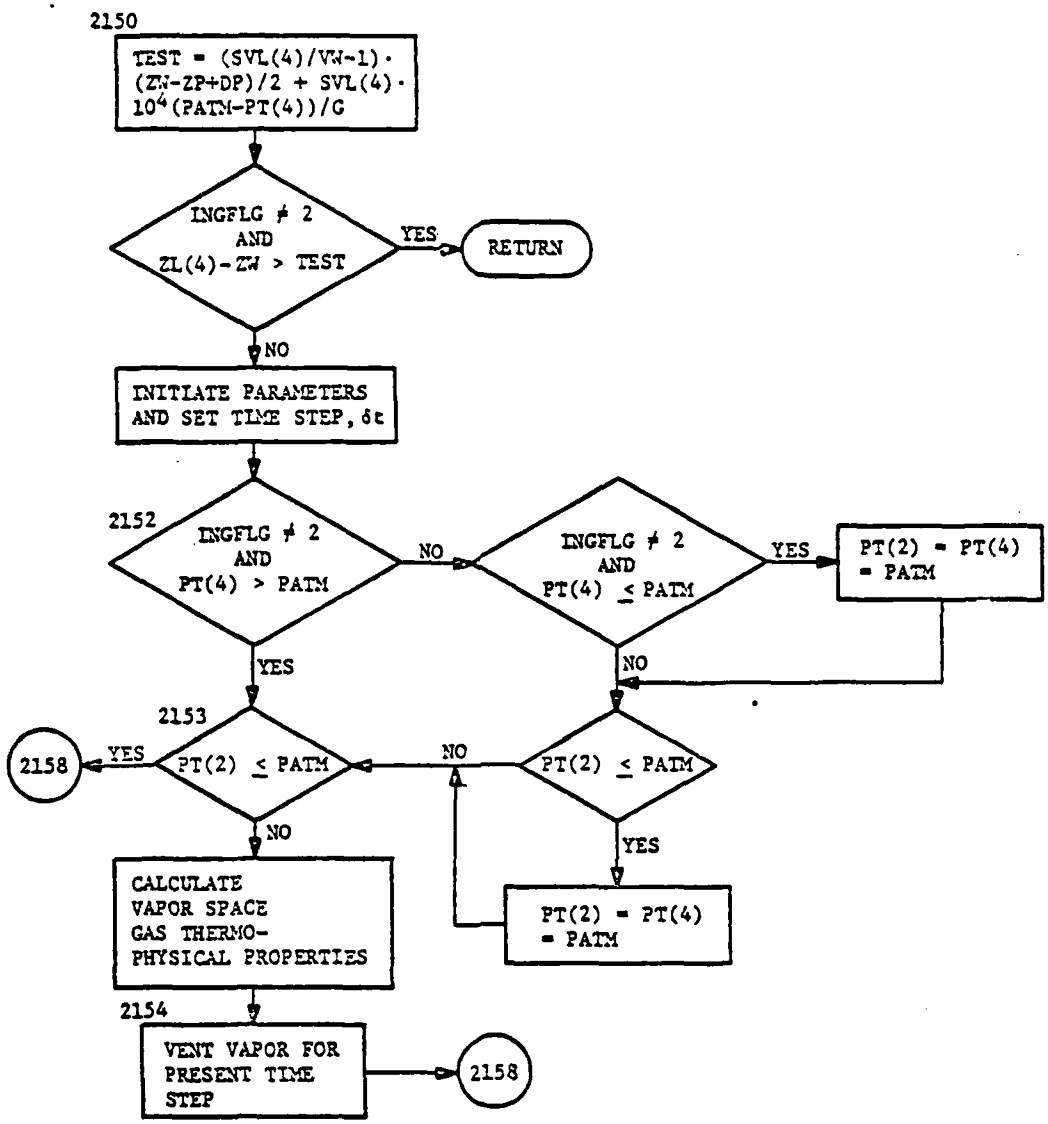


FIGURE C-9. SUBROUTINE INGEST FLOW CHART (Cont'd)

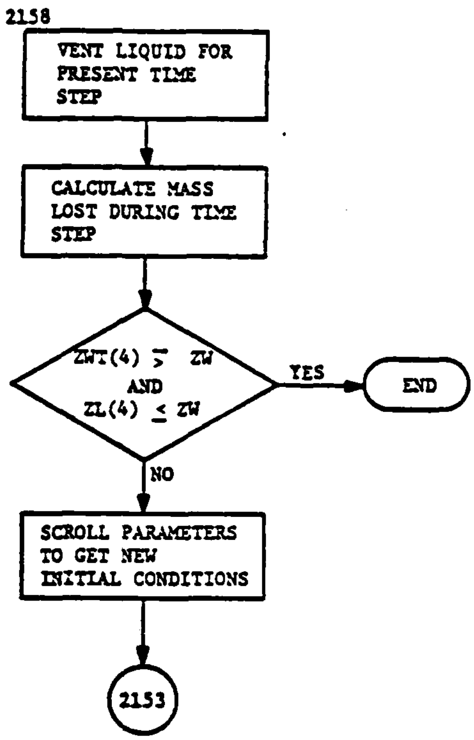


FIGURE C-9. SUBROUTINE INGEST FLOW CHART (Cont'd)

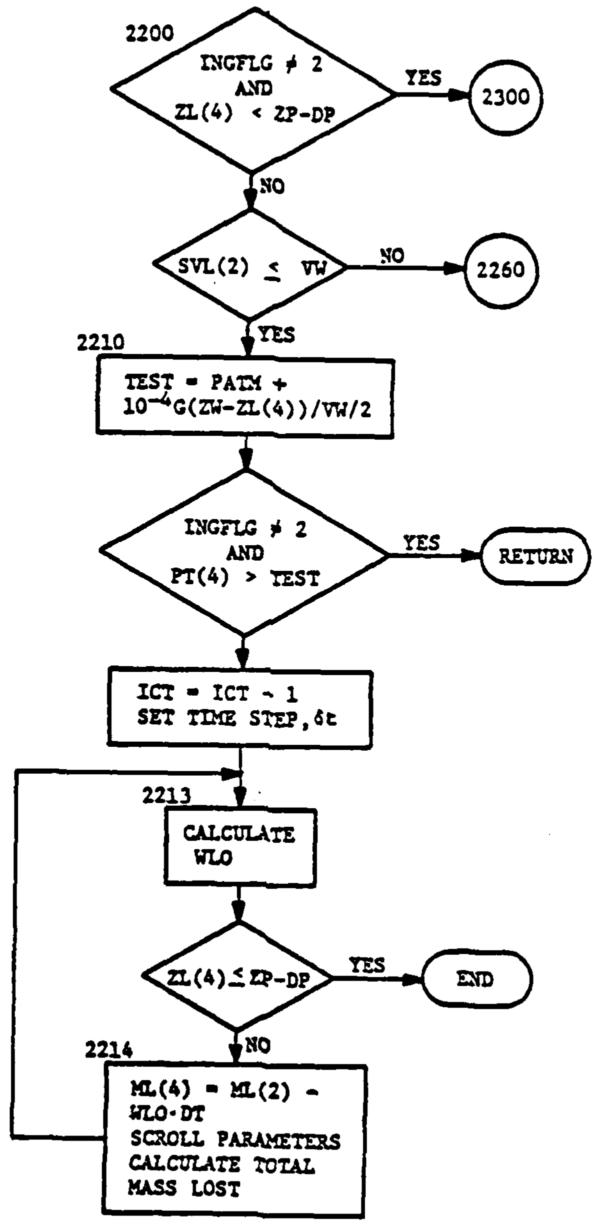


FIGURE C-9. SUBROUTINE INGEST FLOW CHART (Cont'd)

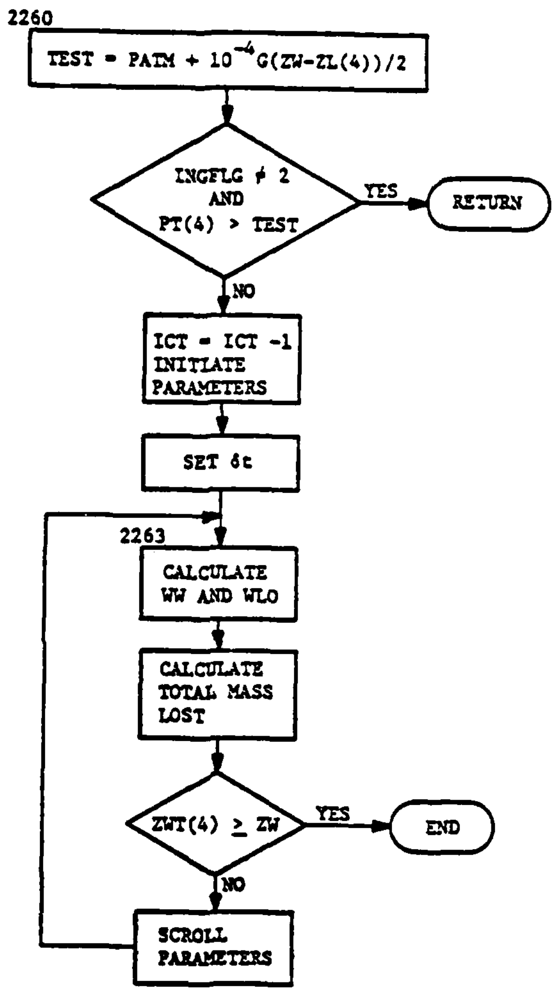


FIGURE C-9. SUBROUTINE INGEST FLOW CHART (Cont'd)

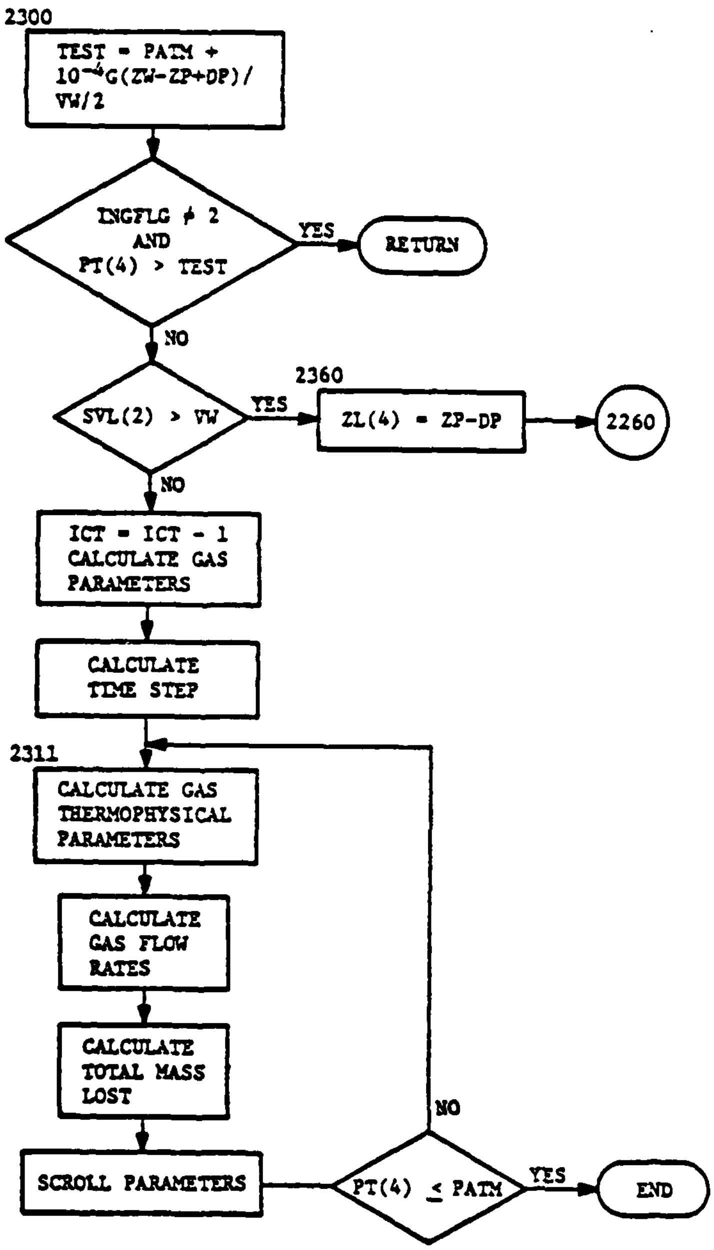


FIGURE C-9. SUBROUTINE INGEST FLOW CHART (Concl'd)

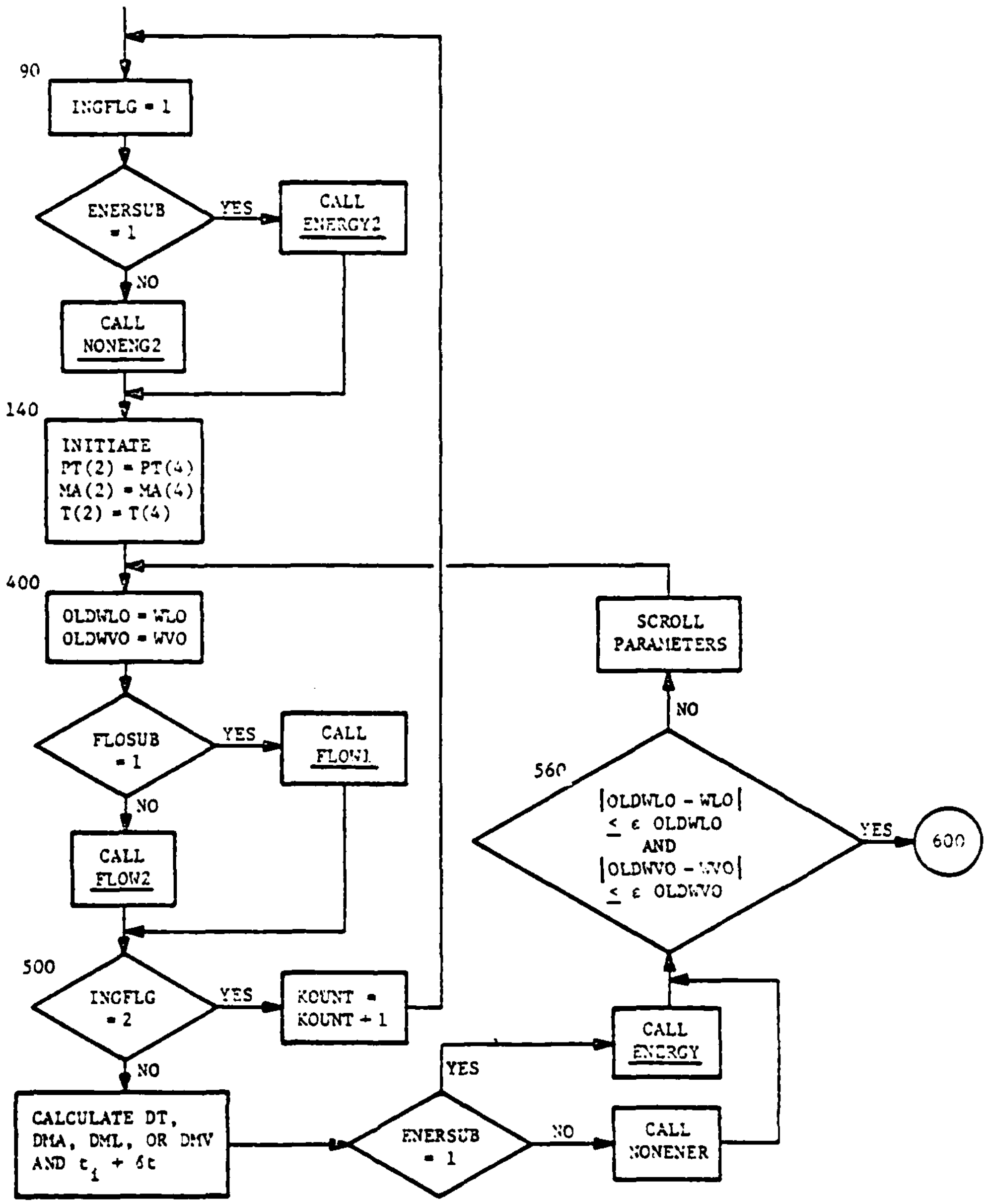


FIGURE C-10. SUBROUTINE AIRIN (ITIME) FLOW CHART

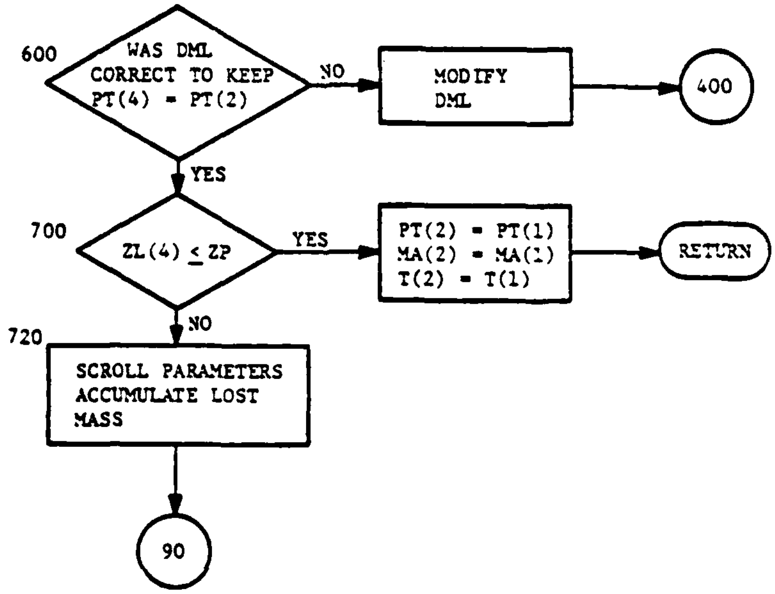


FIGURE C-10. SUBROUTINE AIRIN (ITIME) FLOW CHART
(Concl'd)

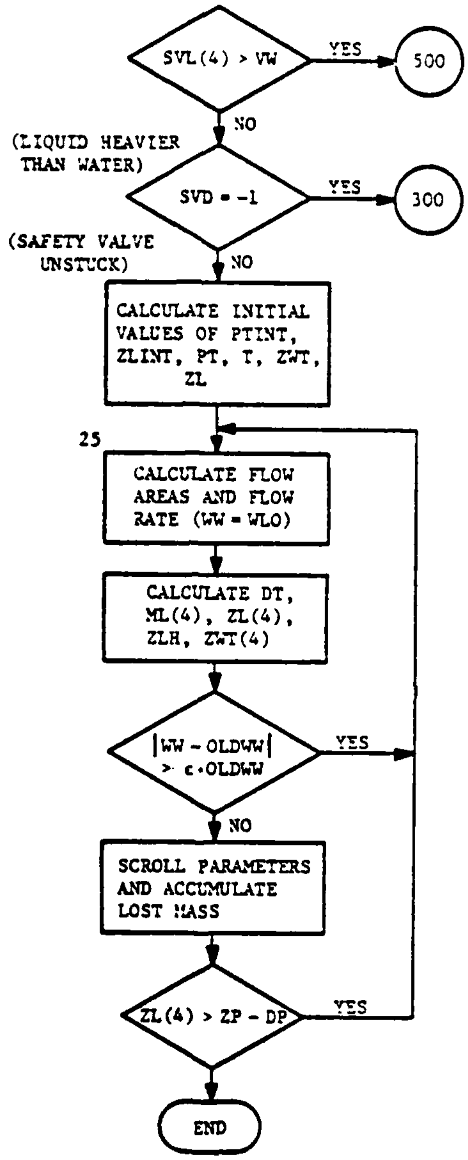


FIGURE C-11. SUBROUTINE WATIN FLOW CHART

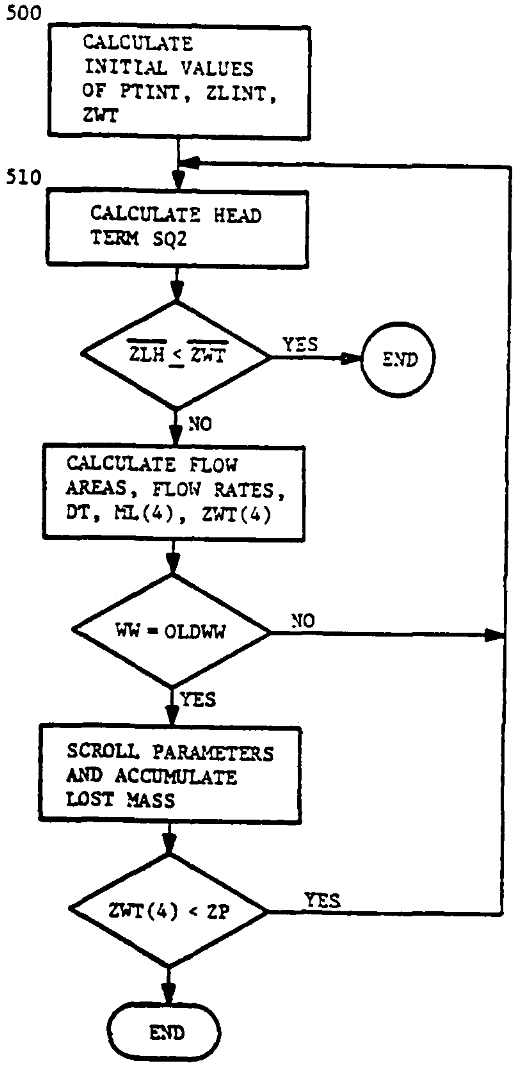


FIGURE C-11. SUBROUTINE WATIN FLOW CHART
(Cont'd)

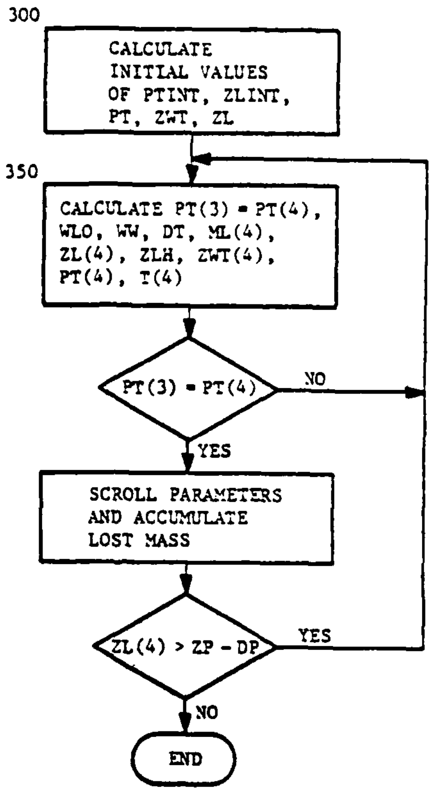


FIGURE C-11. SUBROUTINE WATIN FLOW CHART
(Concl'd)

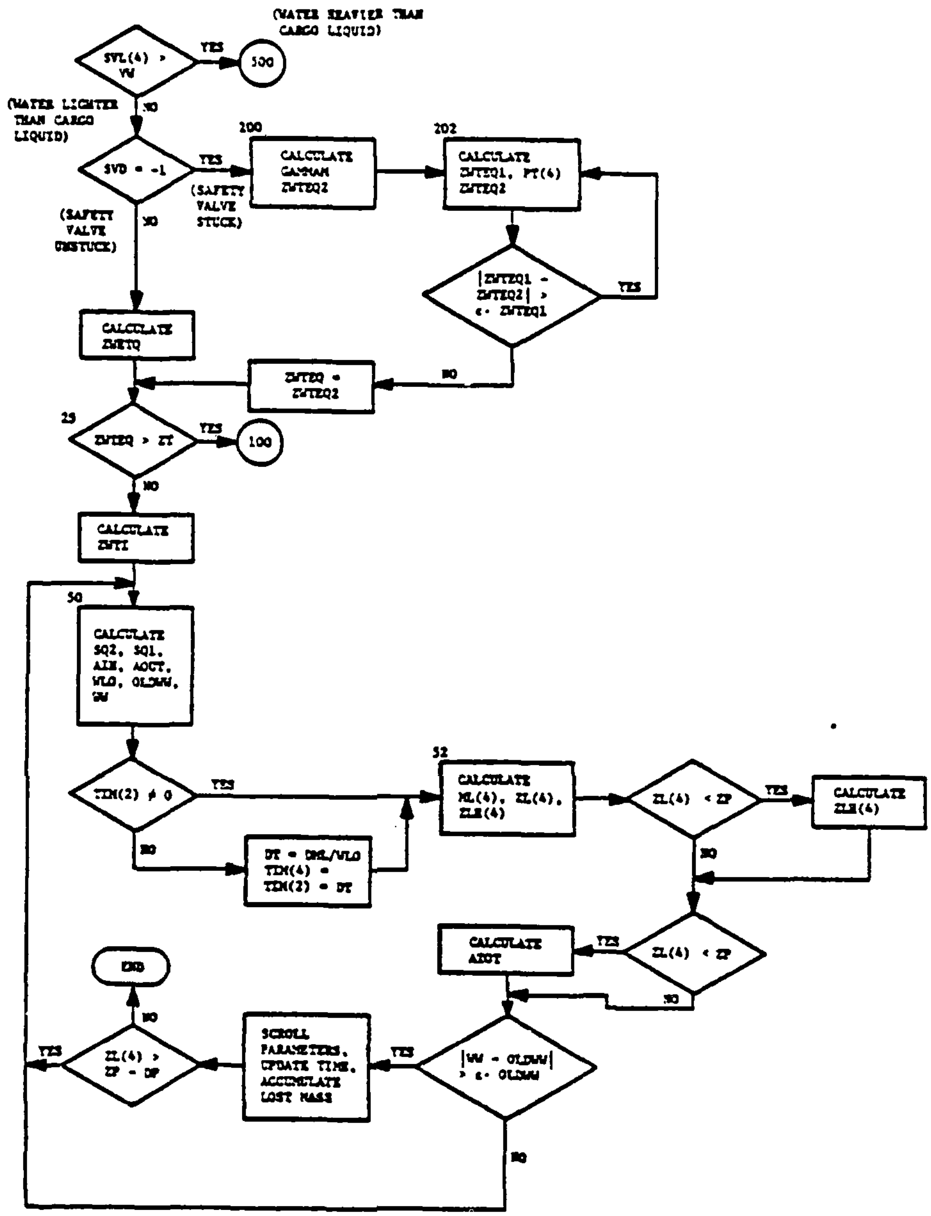


FIGURE C-12. SUBROUTINE NOOUT FLOW CHART

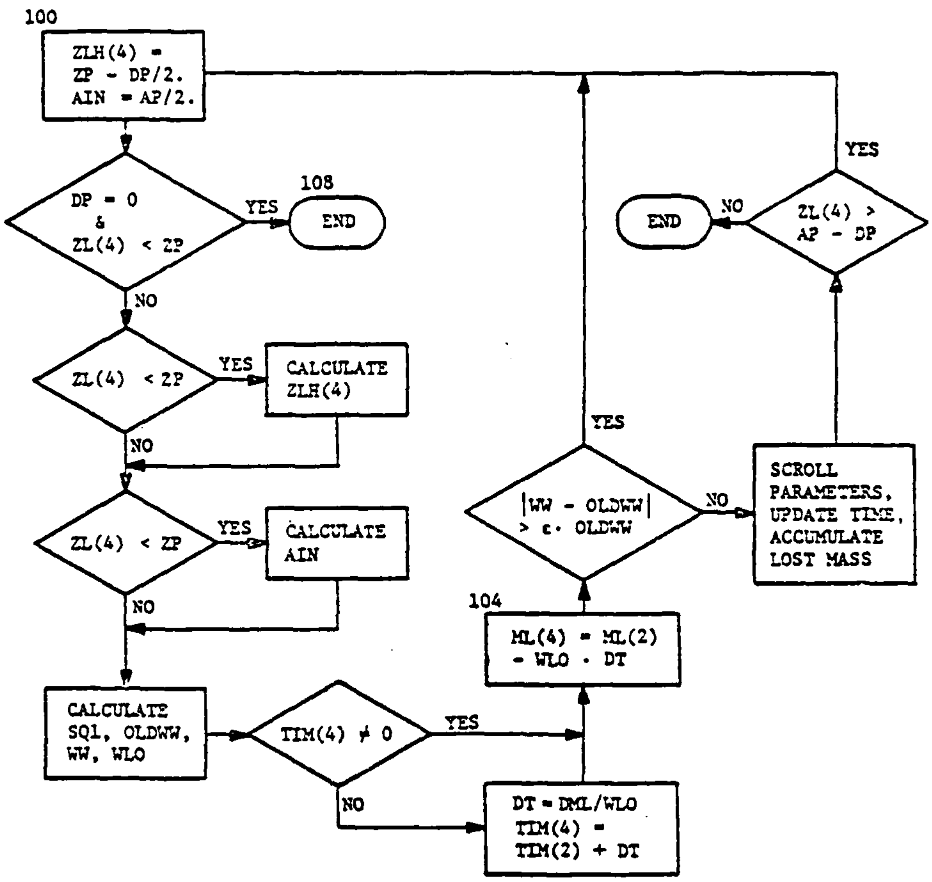


FIGURE C-12. SUBROUTINE NOOUT FLOW CHART
(Cont'd)

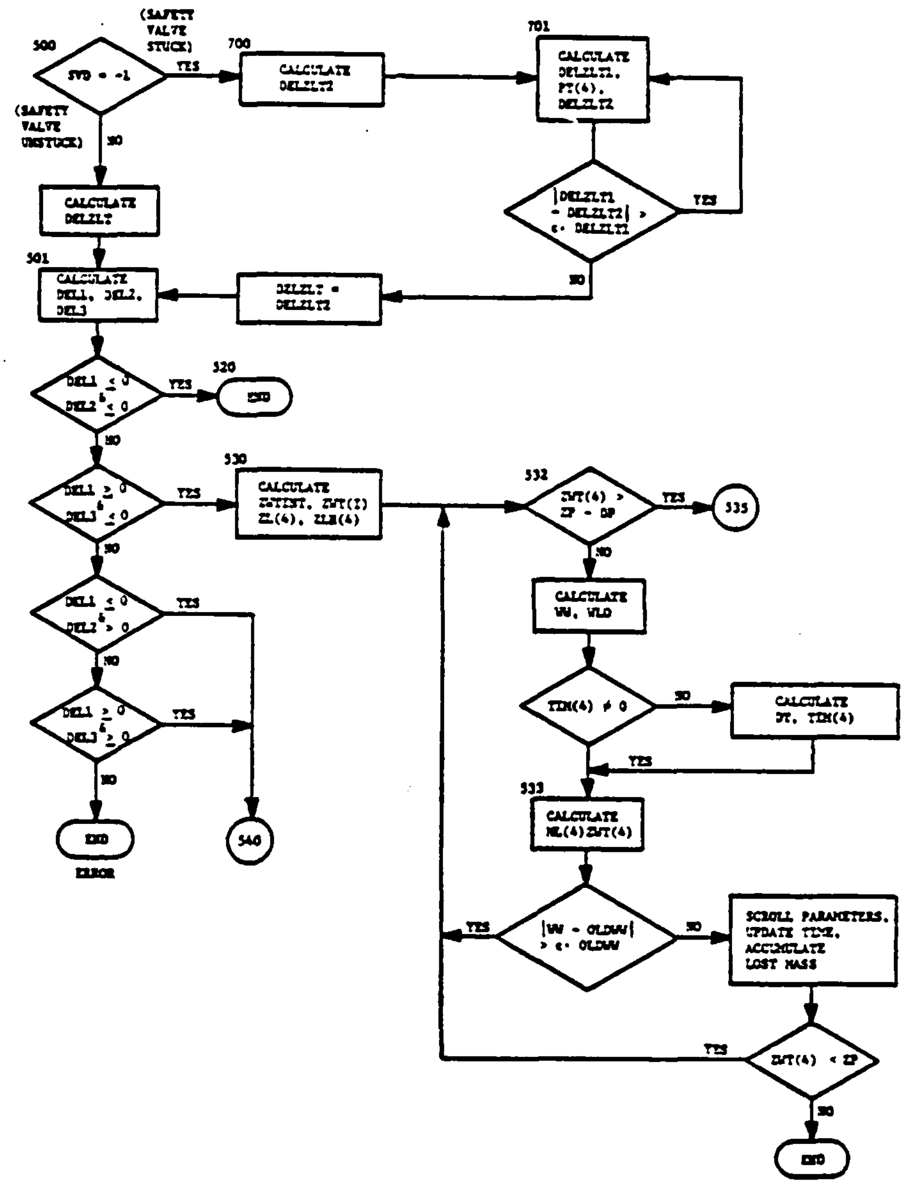


FIGURE C-12. SUBROUTINE NOOUT FLOW CHART
(Cont'd)

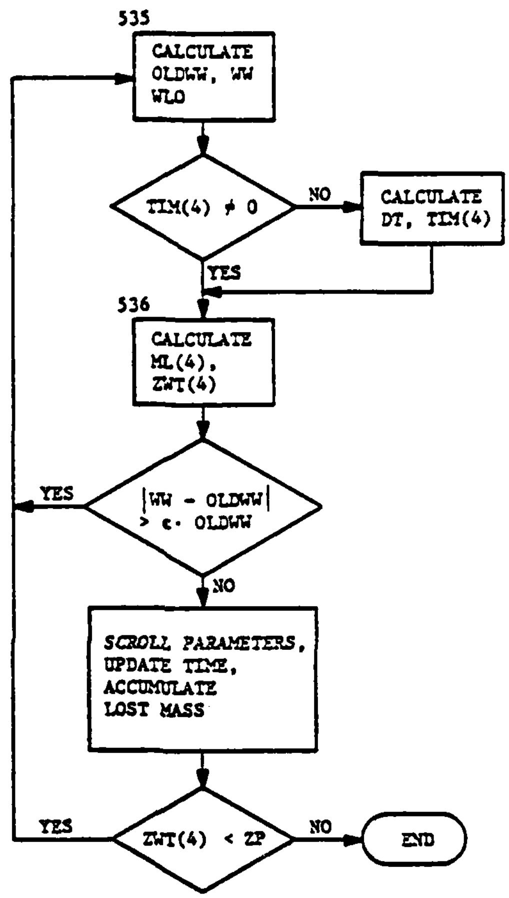


FIGURE C-12. SUBROUTINE NOOUT FLOW CHART
(Cont'd)

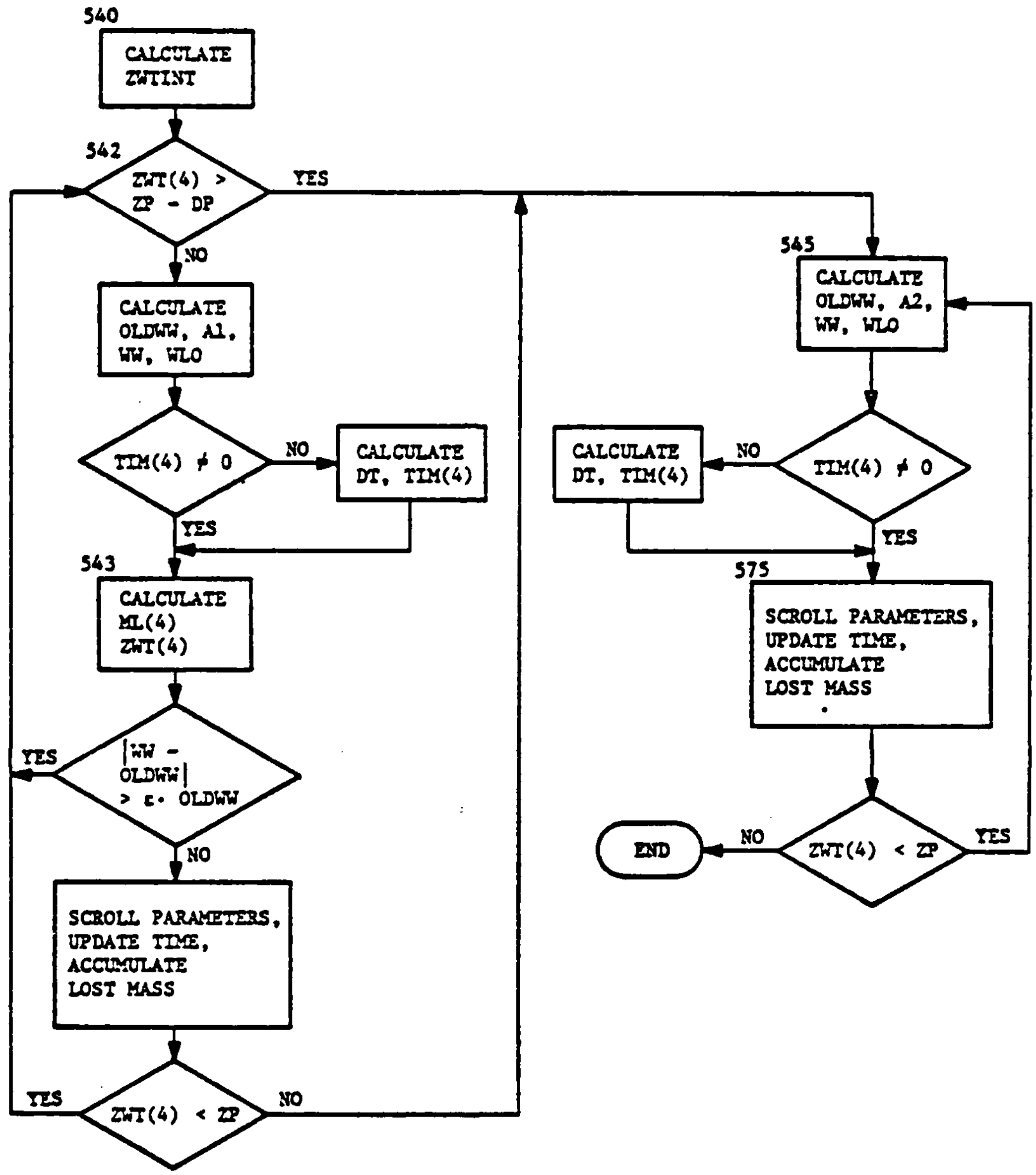


FIGURE C-12. SUBROUTINE NOOUT FLOW CHART
(Concl'd)

TABLE C.1. VENTING RATE MODEL INPUT

1. Cargo identification code (to be used eventually with the HACS Chemical Properties File)
2. Cargo molecular weight
3. Total initial mass of cargo, grams
4. Cargo initial temperature, °C
5. Volatility constant; used in determining whether the energy balance for volatile or nonvolatile cargos will be used, by comparing saturation pressure at the cargo initial temperature to (volatility constant) times (atmospheric pressure); a value of 0.8 has been found acceptable.
6. Air temperature, °C
7. Air pressure, KPa (Standard Atmosphere = 101.4 KPa)
8. Tank volume, cm^3
9. Tank height, cm
10. Estimate of tank pressure, KPa; is compared to atmospheric pressure and initial estimate of tank pressure is set to larger of the two.
11. Puncture description: round, horizontal, or vertical slot
12. Height of puncture above tank bottom, cm
13. Puncture area, cm^2
14. Puncture width, if horizontal or vertical slot, cm
15. Puncture discharge coefficient
16. Safety valve condition: stuck or unstuck
17. Safety valve vacuum differential setting, if unstuck, KPa
18. Height of outside water above tank bottom, cm

19-24. Constants in thermodynamic property correlations for vapor pressure (KPa), liquid density (g/cm^3), vapor compressibility (-), liquid specific heat (cal/g-°C), vapor specific heat (cal/g-°C), and latent heat of evaporation (cal/g).

25. Descriptor for adiabatic or isothermal conditions.

TABLE C-2. MISCELLANEOUS SUBPROGRAMS

SUBROUTINE AIRMASS:

Uses ideal gas equation of state to determine mass of air in the cargo tank vapor space.

SUBROUTINE CORRECT:

Updates latent heat, specific volume of vapor, specific volume of liquid, liquid specific heat, and vapor specific heat with the most recent value of temperature at time t_{i+1}.

FUNCTION CPLHF (T):

Computes the latent heat of vaporization of the cargo liquid with temperature, T.

FUNCTION GAMM (RA):

Computes the average value of the ratio of specific heats of the vapor space gases (cargo vapor and, when present, air). The average is taken over times t_i and t_{i+1}.

SUBROUTINE TERMIN (END CODE):

A terminal printout of time, mass, pressure, height, and temperature. TERMIN is entered from another subprogram that is identified by the name given by the Hollerith Field designated by the parameter end code.

SUBROUTINE ZLHCALC:

Computes the flow center height, ZLH.

TABLE C-3. CPF (IFLAG,T) FUNCTION SUBPROGRAM

IFLAG - Integer to describe which thermophysical property is to be determined

T - Independent parameter

IFLAG	T	CPF
1	Cargo Temperature	Cargo Material Vapor Pressure, $P = f(T)$
2	Cargo Temperature	Cargo Material Liquid Density
3	Cargo Temperature	Cargo Vapor Compressibility Factor, Z
4	Cargo Temperature	Cargo Material Liquid Specific Heat
5	Cargo Temperature	Cargo Material Saturated Vapor Specific Heat at Constant Pressure
6	Cargo Material Vapor Pressure	Cargo Temperature, $T = f^{-1}(P)$

TABLE C-4. SUBROUTINE INGEST FLAG PARAMETERS

One key parameter that determines the computational process is called INGFLG. Values that INGFLG can have and the effect on computation progression are given below:

INGFLG	RESULT
0	Uninterrupted venting - normal mode. Adequate pressure within the tank for liquid cargo and/or gas (cargo vapor and possibly air) to vent through the tank puncture.
2	Insufficient pressure within the tank to vent to the outside media (air and/or water). Initiated in subroutine FLOW1 or FLOW2. Used as a transfer flag to route computation process to subroutine INGEST. INGFLG will be changed to another appropriate value in INGEST.
1	Initiated in subroutine INGEST to route computation process to subroutine AIRIN. If INGFLG is set to 1 in INGEST, return from INGEST to the main program, TVENT, is followed by a call to subroutine AIRIN. Return to TVENT from AIRIN causes INGFLG to be reset to 0.
3	Initiated in subroutine INGEST. Causes return to the main program, TVENT, and an immediate call to subroutine WATIN.
4	Initiated in subroutine INGEST. Causes return to the main program, TVENT, and an immediate call to subroutine NOOUT.
5	Initiated in subroutine INGEST. Causes air to be admitted to the vapor space in the tank instantaneously. Return to the main program, TVENT, follows, whereupon in TVENT, INGFLG is reset to 0 and the cargo release loop is reentered.

TABLE C.5. LIST OF VARIABLES IN COMPUTER PROGRAM

Variable	Units	Common Label	Description	Routines Where Referenced
AIRK	—	ING	Air bubble volume coefficient	TVENT, AIRIN
AOG	cm^2	GEN	Area of gas flow	TVENT, FLOW1, FLOW2, INGEST
AOL	cm^2	GEN	Area of liquid flow	TVENT, FLOW1, FLOW2
AP	cm^2	ING	Area of puncture	TVENT, AIRIN, NOOUT, WATIN
AT	cm^2	GEN	Tank cross-sectional area	TVENT, AIRMASS, ENERGY, ENERGY2, INGEST, NONENER, NONENG2, NOOUT, WATIN
C1, C2	—	CP	Constants used in calculating specific heat of cargo	TVENT, CPF
CDORF (CD)	—	GEN	Discharge coefficient	TVENT, FLOW1, FLOW2, INGEST, NOOUT, WATIN
CMI	g	GEN	Initial cargo mass	TVENT
CMWT (MOLE)	$\frac{g}{g-mole}$	GEN	Cargo molecular weight	TVENT, AIRMASS, CHOKTST, CORRECT, ENERGY, ENERGY2, FLOW1, FLOW2, GAMM, INGEST, NONENER, NONENG2
CPA	$\frac{cal}{g-°C}$	GEN	Specific heat of air	TVENT, ENERGY, ENERGY2, FLOW1, FLOW2, GAMM, INGEST
CPL	$\frac{cal}{g-°C}$	GEN	Specific heat of cargo liquid	TVENT, AIRIN, CORRECT, ENERGY, ENERGY2, GAMM, INGEST, WATIN
CPVBAR	$\frac{cal}{g-°C}$	GEN	Specific heat of cargo vapor	TVENT, AIRIN, CORRECT, ENERGY, ENERGY2, GAMM, INGEST, WATIN
D1, D2	—	CP	Constants used in calculating liquid density	TVENT, CPF
DELTIME	g	ING	Evaporated mass per time step	TVENT, ENERGY, ENERGY2, NOOUT
DMA	g	ING	Mass of air released per time step	TVENT, AIRIN, ENERGY, NONENER
DML	g	ING	Mass of liquid released per time step	TVENT, AIRIN, ENERGY, INGEST, NONENER, NOOUT, WATIN

TABLE C.5. LIST OF VARIABLES IN COMPUTER PROGRAM (Cont'd)

Variable	Units	Common Label	Description	Routines Where Referenced
DMV	g	ENG	Mass of vapor released per time step	TVENT, AIRIN, ENERGY, INGEST, NONENER
DP	cm	ENG	Vertical extent of vertical slots	TVENT, ENERGY, INGEST, NONENER, NOOUT, WATIN, ZLRCALC
DPV (DELPVAL)	KPa	GEN	Safety valve relief vacuum setting	TVENT, ENERGY, INGEST, NONENER
ENRSUB	—	ENG	Selects energy subroutine	TVENT, AIRIN
FLOSUB	—	ENG	Selects flow subroutine	TVENT, AIRIN, CHOKTST
G	$\frac{cm}{sec^2}$	GEN	Gravitational acceleration	TVENT, AIRIN, FLOW1, FLOW2, INGEST, NOOUT, WATIN
H1 → H7	—	CP	Constants for latent heat of cargo	TVENT, CPLHF
HTD (IHEATTR)	—	GEN	Heat transfer descriptor	TVENT, ENERGY, ENERGY2, INGEST, NONENER, NONENG2, WATIN
ICT	—	ENG	Time step counter	TVENT, INGEST
INGFLG	—	ENG	Subroutine flag used in INGEST	TVENT, AIRIN, ENERGY, FLOW1, FLOW2, INGEST, NONENER
J	$\frac{g\text{-}cm^2}{cal\text{-}sec^2}$	GEN	Mechanical equivalent of heat	TVENT, AIRMASS, FLOW1
LAMBDA	$\frac{cal}{g}$	GEN	Latent heat of cargo	TVENT, CORRECT, ENERGY, ENER2
MA	g	GEN	Air mass in tank	TVENT, AIRIN, AIRMASS, ENERGY, ENERGY2, FLOW1, FLOW2, GAMM, INGEST, NONENER, NONENG2, NOOUT, TERMIN, WATIN
ML	g	GEN	Liquid mass in tank	TVENT, AIRIN, AIRMASS, CORRECT, ENERGY, ENERGY2, INGEST, NONENER, NONENG2, NOOUT, TERMIN, WATIN
MV	g	GEN	Vapor mass in tank	TVENT, AIRIN, AIRMASS, CORRECT, ENERGY, ENERGY2, FLOW1, FLOW2, GAMM, INGEST, NONENER, NONENG2, NOOUT, TERMIN, WATIN

TABLE C.5. LIST OF VARIABLES IN COMPUTER PROGRAM (Cont'd)

Variable	Units	Common Label	Description	Routines Where Referenced
NTEST	—	ING	Loop counter through main program	TVENT, INGEST
P1 - P3	—	CP	Constants for calculating vapor pressure	TVENT, CHOKTST, CPF
PA	KPa	GEN	Air pressure in the tank	TVENT, AIRIN, ENERGY, WATIN
PATM	KPa	GEN	Atmospheric pressure	TVENT, ENERGY, INGEST, NONENER
PINF	KPa	GEN	Ambient pressure external to puncture	TVENT, CHOKTST, FLOW1, FLOW2, INGEST, NOOUT
PINFG	KPa	GEN	Ambient pressure external to puncture for gas flow	TVENT, CHOKTST, FLOW1, FLOW2
PT	KPa	GEN	Tank pressure	TVENT, AIRIN, AIRMASS, CHOKTST, CORRECT, ENERGY, ENERGY2, FLOW1, FLOW2, INGEST, NONENER, NONENG2, NOOUT, TERMIN, WATIN
PTEQI	KPa	WAT	Tank pressure at equilibrium	TVENT, INGEST, WATIN
PV	KPa	GEN	Vapor pressure in the tank	TVENT, AIRIN, AIRMASS, CHOKTST, CORRECT, ENERGY, ENERGY2, INGEST, NONENER, NONENG2, NOOUT, TERMIN, WATIN
RG	$\frac{KPa-cm^3}{g\text{-mole-}^\circ K}$	GEN	Universal gas constant, mechanical units	TVENT, AIRMASS, CHOKTST, CORRECT, ENERGY, ENERGY2, FLOW1, FLOW2, GAMM, INGEST, NONENER, NONENG2, NOOUT, WATIN
RG1	$\frac{cal}{g\text{-mole-}^\circ K}$	GEN	Universal gas constant, thermal units	TVENT, FLOW1, FLOW2, GAMM, INGEST
SVA	$\frac{cm^3}{g}$	GEN	Specific volume of air	TVENT, ENERGY2, NONENG2
SVD (IVALVE)	—	GEN	Safety valve descriptor	TVENT, ENERGY, INGEST, NONENER, NOOUT, WATIN
SVL (VL)	$\frac{cm^3}{g}$	GEN	Specific volume of liquid	TVENT, AIRIN, CORRECT, ENERGY, ENERGY2, INGEST, NONENER, NONENG2, NOOUT, WATIN

TABLE C.5. LIST OF VARIABLES IN COMPUTER PROGRAM (Cont'd)

Variable	Units	Common Label	Description	Routines Where Referenced
SVV (VV)	$\frac{cm^3}{g}$	GEN	Specific volume of vapor	TVENT, AIRIN, CHOKTST, CORRECT, ENERGY, ENERGY2, INGEST, WATIN
T	°C	GEN	Cargo temperature	TVENT, AIRIN, AIRMASS, CHOKTST, CORRECT, CPF, CPLHF, ENERGY, ENERGY2, FLOW1, FLOW2, GAMM, INGEST, NONENER, NONENG2, NOOUT, TERMIN, WATIN
TC	°C	GEN	Initial cargo temperature	TVENT, NONENER, NONENG2
TIME (TIM)	sec	GEN	Time	TVENT, AIRIN, ENERGY, INGEST, NOOUT, TERMIN, WATIN
TINF (TATM)	°C	GEN	Air temperature	TVENT, ENERGY, ENERGY2
TMA	g	ING	Total mass of air released from tank	TVENT, AIRIN, INGEST, NOOUT, TERMIN, WATIN
TML	g	ING	Total mass of liquid released from tank	TVENT, AIRIN, INGEST, NOOUT, TERMIN, WATIN
TMV	g	ING	Total mass of vapor released from tank	TVENT, AIRIN, INGEST, NOOUT, TERMIN, WATIN
V1 → V3	—	CP	Constants used in calculating specific heat of vapor	TVENT, CPF
VOLB	cm^3	ING	Volume of air bubble	TVENT, AIRIN, ENERGY2, NONENG
VT (VOLT)	cm^3	GEN	Tank volume	TVENT, AIRMASS, ENERGY, ENERGY2, INGEST, NONENER, NONENG2, NOOUT, WATIN
VW	$\frac{cm^3}{g}$	GEN	Specific volume of water	TVENT, INGEST, NOOUT, WATIN
WAO	$\frac{g}{sec}$	GEN	Discharge rate of air released	TVENT, AIRIN, ENERGY, ENERGY2, FLOW1, FLOW2, INGEST, NONENER, NONENG2
WLO	$\frac{g}{sec}$	GEN	Discharge rate of liquid released	TVENT, AIRIN, ENERGY, ENERGY2, FLOW1, FLOW2, INGEST, NONENER, NONENG2, NOOUT, WATIN
WVO	$\frac{g}{sec}$	GEN	Discharge rate of vapor released	TVENT, AIRIN, ENERGY, ENERGY2, FLOW1, FLOW2, INGEST, NONENER, NONENG2

TABLE C.5. LIST OF VARIABLES IN COMPUTER PROGRAM (Concl'd)

Variable	Units	Common Label	Description	Routines Where Referenced
XLP	cm	ING	Slot width	TVENT, INGEST, NOOUT
Z1 - Z3	—	CP	Constants used for calculating vapor compressibility	TVENT, CPF
ZL	cm	GEN	Height of liquid inside tank	TVENT, AIRIN, AIRMASS, ENERGY, ENERGY2, FLOW1, FLOW2, INGEST, NONENER, NONENG2, NOOUT, TERMIN, WATIN, ZLHCALC
ZLEQI	cm	WAT	Equilibrium height of liquid in the tank	TVENT, INGEST, WATIN
ZLH	cm	GEN	Height of center of flow through puncture	TVENT, AIRIN, ENERGY, ENERGY2, FLOW1, FLOW2, INGEST, NONENER, NONENG2, NOOUT, WATIN, ZLHCALC
ZP	cm	GEN	Puncture height	TVENT, AIRIN, ENERGY, INGEST, NONENER, NOOUT, WATIN, ZLHCALC
ZT	cm	GEN	Tank height	TVENT, INGEST, NOOUT
ZW	cm	GEN	Height of water outside tank	TVENT, INGEST, NOOUT, ZLHCALC
ZWT	cm	ING	Height of water inside tank	TVENT, INGEST, NOOUT, WATIN

TABLE C.6. FORMAT FOR INPUT DATA TO TVENT PROGRAM

Data may be input to the TVENT program through a series of 13 input card sets. Each series corresponds to one data case. Multiple cases may be tested by making only one run of TVENT. To run more than one case, replace the INPUT CARD THIRTEEN (end-of-file card) with an end-of-record card (a 7-8-9 punch in column one). Then repeat the series of 13 input card sets for each case to be tested. For the last case use the INPUT CARD SET THIRTEEN instead of the end-of-record card.

INPUT CARD SET ONE (READ (12,5000) CID, CMWT, CMI, TC, CVOL)

Input the cargo parameters using the standard FORTRAN format statement: FORMAT (A3, 7X, 6E10.0).

Variable		Description	Units
1.	CID	Cargo identification	--
2.	CMWT	Cargo molecular weight	gram/gram-mole
3.	CMI	Initial mass of cargo	gram
4.	TC	Initial cargo temperature	°C
5.	CVOL	Constant used in calculating volatility of cargo	—

INPUT CARD SET TWO (READ (12,5005) ZT, VT, PTI, HTD)

Input the tank parameters using the input format: FORMAT (3E10.0,I3).

Variable		Description	Units
1.	ZT	Tank height	cm
2.	VT	Tank volume	cm^3
3.	PTI	Initial tank pressure	KPa
4.	HTD	Heat transfer descriptor: 1 = Insulated walls (ADIABATIC process) -1 = Isothermal walls (ISOTHERMAL process)	--

INPUT CARD SET THREE (READ 12,5020) PDTSC, ZP, AP, XLP, CDORF)

Input the puncture parameters using the input format: FORMAT (1I10, 4E10.0).

TABLE C.6. FORMAT FOR INPUT DATA TO TVENT PROGRAM
(Cont'd)

Variable		Description	Units
1.	PDTSC	Puncture descriptor: 1 = Round hole 2 = Horizontal slot 3 = Vertical slot	--
2.	ZP	Puncture height	cm
3.	AP	Puncture area	cm^2
4.	XLP	Width of vertical slots (Note: Enter zero for round holes or horizontal slots)	cm
5.	CDORF	Discharge coefficient	--

INPUT CARD SET FOUR (READ 12,5030) SVD, DPV)

Input the safety valve parameters using the input format: FORMAT (1I10, 1E10.0).

Variable		Description	Units
1.	SVD	Safety valve descriptor: 1 = Unstuck -1 = Stuck	--
2.	DPV	Safety valve relief setting	KPa

INPUT CARD SET FIVE (READ (12,5010) TINF, PATM)

Input the air properties using the input format: FORMAT (8E10.0).

Variable		Description	Units
1.	TINF	Air temperature	°C
2.	PATM	Atmospheric pressure	KPa

Input card sets 6 through 11 contain the chemical property file constants used in FUNCTION CPF and FUNCTION CPLHF. The variable T denotes the temperature in °C in the following formulas.

TABLE C.6. FORMAT FOR INPUT DATA TO TVENT PROGRAM
(Concl'd)

INPUT CARD SET SIX (READ (12,5010) P1, P2, P3)

Input the vapor pressure constants using the input format: FORMAT (8E10.0).

INPUT CARD SET SEVEN (READ (12,5010) D1, D2)

Input the liquid density constants using the input format: FORMAT (8E10.0).

INPUT CARD SET EIGHT (READ (12,5010) Z1, Z2, Z3)

Input the vapor compressibility constants using the input format: FORMAT (8E10.0).

INPUT CARD SET NINE (READ (12,5010) C1, C2)

Input the specific heat of cargo constants using the input format: FORMAT (8E10.0).

INPUT CARD SET TEN (READ (12,5010) V1, V2, V3)

Input the specific heat of vapor constants using the input format: FORMAT (8E10.0).

INPUT CARD SET ELEVEN (READ (12,5010) H1, H2, H3, H4, H5, H6, H7)

Input the latent heat of cargo constants using the input format: FORMAT (8E10.0).

INPUT CARD SET TWELVE (READ (12,5010) ZW, VW)

Input the water characteristics using the input format: FORMAT (8E10 (8E10.0).

Variable	Description	Units
1. ZW	Height of water outside of tank	cm
2. VW	Specific volume of water	cm^3/gram

INPUT CARD SET THIRTEEN (End-of-file card)

This card ends the data used by TVENT. Input a 6-7-8-9 punch in card column 1 for the end-of-file.

```
      PROGRAM TVENT(INPUT,OUTPUT,TAPE9=INPUT,TAPE12=OUTPUT)
C
C     CHEMICAL PROPERTIES COEFFICIENTS
      COMMON /CP/ P1,P2,P3,D1,D2,Z1,Z2,Z3,C1,C2,V1,V2,V3,
     1            H1,H2,H3,H4,H5,H6,H7
      COMMON /GEN/ PT(4),T(4),ZL(4),ZLH(4),MA(4),MV(4),ML(4),PINF,
     1            VW,G,J,CDONF,AOL,AOG,RG1,RG,TINF,TIME(4),CMWT,
     2            VT,ZW,ZP,DPV,SVD,HTD,CPA,SVL(4),SVV(4),WLO,WVO,
     3            WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),TC,SVA,
     4            PINIG,Z1,CMI,PA(4)
      COMMON/ING/  DP,TML,TMV,TMA,DML,DMV,DMA,FLOSUB,ENRSUB,AP,INGFLG,
     1            ICT,XLP,DELTML,ZWT(4),VOLU,NTEST,NCHANGE
      COMMON/WAT/  ZLEQI,PIEQI
      COMMON /WNAME/ NOWVO
      INTEGER  HTD,PDTSC,PE,SVD,FLOSUB,ENRSUB
      REAL ML,MV,MA,J,LAMBDA
C   *** DEFINITION OF INPUT DATA ***
C       SYMBOL      DESCRIPTION                       UNITS
C        AP         PUNCTURE AREA                     CM**2
C        AT         TANK SURFACE AREA                 CM**2
C        CDONF      DISCHARGE COEFFICIENT             --
C        CID        CARGO ID                          --
C        CMI        INITIAL CARGO MASS                GM
C        CMWT       CARGO MOLECULAR WT                GM/GM-MOLE
C        CVOL       CONST USED TO CALC. VOLATILE      --
C        C1-C2      CONST FOR SP HEAT OF CARGO        --
C        DPV        SAFETY VALVE RELIEF SETTING       KPA
C        D1-D2      CONST FOR LIQUID DENSITY          --
C        HTD        HEAT TRANSFER DESCRIPTOR          --
C                   1 =  ADIABATIC
C                   -1 = ISOTHERMAL
C        H1-H7      CONST FOR LATENT HEATLIQUID       --
C        PDTSC      PUNCTURE DESCRIPTOR               --
C                   1 -  ROUND
C                   2 -  HORIZONTAL
C                   3 -  VERTICAL
C        PTI        INIT TANK PRESSURE                KPA
C        P1-P3      CONST FOR VAPOR PRESSURE          --
C        SVD        SAFETY VALVE DESCRIPTOR           --
C                   1 -  UNSTUCK
C                   -1 = STUCK
C        TC         INITIAL CARGO TEMPERATURE         DEG C
C        TINF       AIR TEMPERATURE                   DEG C
C        VT         TANK  VOLUME                      CM**3
C        VW         SPECIFIC VOLUME OF WATER          CM**3/GM
C        V1-V3      CONST FOR SP HEAT OF VAPOR        --
C        XLP        SLOT WIDTH                        CM
C        ZP         PUNCTURE HEIGHT                   CM
C        ZT         TANK HEIGHT                       CM
C        ZW         HEIGHT OF WATER OUTSIDE           CM
C        Z1-Z3      CONST FOR VAPOR COMPRESSIB.       --
C   *** PROGRAM PARAMETERS ***
C       SYMBOL      DESCRIPTION                       UNITS
C        AOG        AREA OF GAS FLOW                  CM**2
C        AOL        AREA OF LIQUID FLOW               CM**2
C        ENRSUB     SELECTS ENERGY SUBROUTINE         --
C                   1 -  ENERGY
```

```
      C                    2 =  NONENER
      C          FLOSUB    SELECTS FLOW TYPE              --
      C                    1 -  FLOW1
      C                    2 =  FLOW2
      C          HTASC     HEAT TRANSFER DESCRIPTOR       --
      C          MA        AIR MASS                       GM
      C          ML        LIQUID MASS                    GM
      C          MV        VAPOR MASS                     GM
      C          NW        PRINTER DEVICE CODE            --
      C          NR        READER  DEVICE CODE            --
      C          PDASC     PUNCTURE DESCRIPTION           --
      C          PINF      INITIAL VAPOR PRESSURE         KPA
      C          PT        TANK PRESSURE                  KPA
      C          PTI       INITIAL TANK PRESSURE          KPA
      C          SVA       SPECIFIC VOL. AIR              CM**3/GM
      C          SVASC     SAFETY VALVE CONDITION         --
      C          SVL       SPECIFIC VOL. LIQUID           CM**3/GM
      C          SVV       SPECIFIC VOL. VAPOR            CM**3/GM
      C          T         CARGO TEMPERATURE              DEC C
      C          TIME      TIME                           SEC
      C          WAO       FLOW RATE OF AIR RELEASED      GM/SEC
      C          WLO       FLOW RATE OF CARGO RELEASED    GM/SEC
      C          WVO       FLOW RATE OF VAPOR RELEASED    GM/SEC
      C          Z         VAPOR COMPRESSIBILITY          --
      C          ZL        LIQUID HEIGHT                  CM
      C          ZLN       HEIGHT OF FLOW CENTER          CM
      C          ZLI       LIQUID LEVEL                   CM
      C    *** DEFINITION OF CONSTANTS ***
      C         SYMBOL     DESCRIPTION                    UNITS
      C          CPA       SPECIFIC HEAT OF AIR           CAL/GM*DEG C
      C          G         GRAVITATION CONSTANT           CM/SEC**2
      C          J         JOULE'S EQUIVALENCY CONSTANT   GM-CM**2/CAL-S**2
      C          PATM      ATMOSPHERIC PRESSURE           KPA
      C          RG        GAS CONSTANT                   KPA-CM**3/GM MOLE-DEG K
      C          RG1       GAS CONSTANT                   CAL/GM MOLE-DEG K
            ICT=0
            NOWVO=0
      C     NTEST = 0 NO PASSES THROUGH MAIN LOOP
      C     NTEST = 1 AT LEAST ONE PASS THROUGH MAIN LOOP
            NTEST=0
      C     IZERO  IS THE COUNTER FOR RESTARTING THE ITERATIONS WHEN ZL IS ZERO
            IZERO=0
            G=980.5
            RG=8312.75
            RG1=1.986
            J=4.18937
      C     KS= 0 , 1     CALL CHOKTSF
      C     KS= 2         DO NOT CALL CHOKTSF
            KS=0
            CPA=0.2395
      C   *** INPUT SEGMENT ***
            NW=12
            NR=9
      C     CARGO PARAMETERS
            READ(NR,5000)CID,CMWT,CMI,TC,CVOL
            WRITE(NW,6000)
            WRITE(NW,7000)CID,CMWT
```

```
      WRITE(NW,7001) CNI,TC,CVOL
C     TANK PARAMETERS
      READ(NR,5005)ZT,VT,PTI,HTD
      AT=VT/ZT
      HTASC=10HINSULATED
      IF (HTD.EQ.-1) HTASC=10HISOTHERMAL
      WRITE(NW,7010)ZT,AT,VT,PTI,HTASC
C
C     PUNCTURE PARAMETERS
      READ(NR,5020)PDTSC,ZP,AP,XLP,CDORF
      PDASC=10HROUND
      IF (PDTSC.EQ.2) PDASC=10HH. SLOT
      IF (PDTSC.EQ.3) PDASC=10HV. SLOT
      WRITE(NW,7020)PDASC,ZP,AP,XLP,CDORF
C
C     SAFETY VALVE PARAMETERS
      READ(NR,5030)SVD,DPV
      SVASC=10HSTUCK
      IF (SVD.EQ.+1) SVASC=10HUNSTUCK
      WRITE(NW,7030)SVASC,DPV
C
C     AIR PROPERTIES
      READ(NR,5010)TINF,PATM
      PINF1=PINF=PATM
      WRITE(NW,7040)TINF,PATM
C
C     CHEMICAL PROPERTY FILE
C     VAPOR PRESSURE
      READ(NR,5010)P1,P2,P3
      WRITE(NW,7050)P1,P2,P3
C     LIQUID DENSITY
      READ(NR,5010)D1,D2
      WRITE(NW,7060)D1,D2
C     VAPOR COMPRESSIBILITY
      READ(NR,5010)Z1,Z2,Z3
      WRITE(NW,7070)Z1,Z2,Z3
C     SPECIFIC HEAT OF CARGO
      READ(NR,5010)C1,C2
      WRITE(NW,7080)C1,C2
C     SPECIFIC HEAT OF VAPOR
      READ(NR,5010)V1,V2,V3
      WRITE(NW,7090)V1,V2,V3
C     LATENT HEAT OF LIQUID
      READ(NR,5010)H1,H2,H3,H4,H5,H6,H7
      WRITE(NW,7100)H1,H2,H3,H4,H5,H6,H7
C
C     WATER CHARACTERISTICS
      WRITE(NW,710 )
      READ(NR,5010)ZW,VW
      WRITE(NW,7110)ZW,VW
      WRITE(NW,7250)
C
C   *** CALCULATE INITIAL CONDITIONS ***
      INGFLG=0
      IFINF=1
      FLOSUB = 1
      CHRSUB=1
```

```
      DP=0.0
      DELTME=0.0
      IF(PDTSC.EQ.1) DP=AP/XLP
      PVI=CPF(1,TC)
C
C     IS CARGO VOLATILE?
      IF (PVI .GE. PINF*CVOL) GO TO 200
C
C     NON VOLATILE CARGO
C     RELIEF VALVE STUCK?
      IF (SVD.NE.1) GO TO 120
C
C     VALVE NOT STUCK
      PTI=PINF
  100 FLOSUB=2
      ENRSUB=2
      GO TO 250
C
C     VALVE STUCK
  120 PTI=AMAX1(PINF ,PTI)
      GO TO 100
C
C     CARGO VOLATILE
  200 PVI=CPF(1,TC)
C
C     RELIEF VALVE STUCK?
      IF (SVD.NE.1) GO TO 220
C
C     VALVE NOT STUCK
      IF (PVI.GT.DPV) GO TO 220
C     INPUT ERROR
      WRITE(NW,9000)PVI,DPV
      GO TO 4000
C
C     RELIEF VENT STUCK
 220  PTI = AMAX1(PVI,PINF)
C
C     COMPUTE INITIAL LIQUID LEVEL AND MASSES
 250  SVV(1)=SVV(2)=SVV(3)=SVV(4)=CPF(3,TC)*RG*(TC+273.2)/(CMUT*PVI)
      PV(1)=PV(2) PV(3)=PV(4)=PVI
      SVL(1)=SVL(2)=SVL(3)=SVL(4)=1.0/CPF(2,TC)
      SVA=RG*(TINF+273.2)/(28.96*PINF)
      ML(1)=ML(2)=ML(3)=ML(4)=(CMI*SVV(1)-VT)/(SVV(1)-SVL(1))
      MV(1)=MV(2)-MV(3)=MV(4)=CMI-ML(4)
      ZLI=ML(1)*SVL(1)/AT
      IF (ZLI.LT.ZT) GO TO 270
      WRITE(NW,9010)ZLI,ZT,ZT
      ZLI=ZT
  270 ZL(1)=ZL(2)=ZL(3)=ZL(4)=ZLI
      TVL=ZL(1)*AT
      TVV-MV(1)*SVV(1)
      MA(1)=MA(2)-MA(3)=MA(4)=28.96*(PTI-PVI)*TVV/(RG*(TC+273.2))
      TVA=MA(1)*SVA
      PT(1)=PT(2)=PT(3)=PT(4)=PTI
      PA(1)=PA(2)=PA(3)=PA(4)=(MA(4)*RG/28.96*(TC+273.2))/(VT-ML(4)*
     1     SVL(4))
      TIME(1)=TIME(2)=TIME(3)=TIME(4)= 0.
```

```
      T(1)=T(2)=T(3)=T(4)=TC
      CPL(1)=CPL(2)=CPL(3)=CPL(4)=CPF(4,T(4))
      CPVBAR(1)=CPVBAR(2)=CPVBAR(3)=CPVBAR(4)=CPF(5,T(4))
C
      DML=0.
      DMV=0.01*MV(2)
      IF (ZL(1).LT.ZP-DP) GO TO 280
      DML=0.01*ML(2)
      DMV=0.
  280 CONTINUE
      WRITE(NW,7260) ML(1),MV(1),MA(1),SVL(1),SVV(1),SVA,TVL,TVV,TVA,
     1      DML,DMV,ZL(1)
      WRITE(NW,6100)
C
C   *** CARGO RELEASE LOOP ***
C
      L1=0
      WLO=WAO=WVO=0.
      OLDWLO=OLDWVO=0.0
      TML=TMA=TMV=0.0
      WRITE(NW,7270)
      AOG2=AOG3=0.
      AOL2=AOL3=0.
      ZLN2=ZLN3=0.
      CALL INGEST
      IF(INGFLG.EQ.0) GO TO 300
      GO TO 610
  300 CONTINUE
      NCHANGE=0
      ICT=ICT+1
      IF(ICT.GT.5000) GO TO 630
      IF(TIME(2).EQ.0) GO TO 308
      IF(ZL(2).LE.ZP-DP) WLO=0.0
      IF(WLO.GT.0) GO TO 305
      DMV=DMV*((PT(2)-PINFG)/(PT(1)-PINFG))**0.5
      DMV=AMAX1(DMV,0.005*MV(2))
      DML=DMA=0.
      GO TO 308
  305 DML=DML*((PT(2)-PINF+G*1.0E-4*(ZL(2)-ZLN(2))/SVL(2))
     1/(PT(1)-PINF+G*1.0E-4*(ZL(1)-ZLN(1))/SVL(1)))**0.5
      DML=AMAX1(DML,0.002*ML(2))
      DMA=DMV=0.
  308 CONTINUE
C     CONTINUE DISCHARGE
C     DETERMINE FLOW AREAS AND PRESSURES
C**********
C
C             KTYP  DESCRIPTIONS
C     KTYP     CARGO LEVEL                     WATER LEVEL
C
C      1       ABOVE PUNCTURE                  BELOW PUNCTURE
C      2       ABOVE PUNCTURE                  ABOVE PUNCTURE
C      3       ABOVE PUNCTURE                  INTERSECTING PUNCTURE
C      4       INTERSECTING PUNCTURE           BELOW PUNCTURE
C      5       INTERSECTING PUNCTURE           ABOVE PUNCTURE
C      6       INTERSECTING PUNCTURE AND       INTERSECTING PUNCTURE
C              ABOVE WATER LEVEL
```

```
C       7       INTERSECTING PUNCTURE AND      INTERSECTING PUNCTURE
C               BELOW WATER LEVEL
C       8       BELOW PUNCTURE                 BELOW PUNCTURE
C       9       BELOW PUNCTURE                 ABOVE PUNCTURE
C       10      BELOW PUNCTURE                 INTERSECTING PUNCTURE
C
C**********
C
C     PUNCTURE NOT SUBMERGED BY WATER
      IF (ZW.GT.ZP-DP) GO TO 330
C     CARGO BELOW PUNCTURE
      IF (ZL(2).GT.ZP-DP) GO TO 310
      AOG=AP
      AOL=0.
      PINFI=PINFG=PINF=PATM
      KTYP=8
      GO TO 400
C     CARGO ABOVE PUNCTURE
  310 CONTINUE
      IF (ZL(2).LT.ZP) GO TO 320
      AOG=0.
      AOL=AP
      PINFI=PINFG=PINF=PATM
      ZLH(2)=ZP-0.5*DP
      ZLH(4)=ZLH(3)=ZLH(2)
      KTYP=1
      GO TO 400
C     CARGO INTERSECTS PUNCTURE
  320 CONTINUE
      AOL=AP*(ZL(2)-ZP+DP)/DP
      AOG=AP-AOL
      ZLH(2)=0.5*(ZL(2)+ZP-DP)
      ZLH(4)=ZLH(3)=ZLH(2)
      PINFI=PINFG=PINF=PATM
      KTYP=4
      GO TO 400
C
C   ***
C     PUNCTURE SUBMERGED BY WATER
  330 CONTINUE
      IF (ZW.LT.ZP)  GO TO 360
C     CARGO BELOW PUNCTURE
      IF (ZL(2).GT. ZP-DP) GO TO 340
      AOG=AP
      AOL=0.
      PINFI=PINFG=PINF=PATM+1.E-4*G*(ZW-ZP+DP*0.5)/VW
      KTYP=9
      GO TO 400
C     CARGO ABOVE PUNCTURE
  340 CONTINUE
      IF (ZL(2).LT.ZP) GO TO 3.0
      AOG=0.
      AOL=AP
      ZLH(2)=ZP-DP*0.5
      ZLH(4)=ZLH(3)=ZLH(2)
      PINFI= PINFG-PINF=PATM+1.0E-4* G*(ZW-ZLH(2))/VW
      KTYP=2
```

```
      GO TO 400
C     CARGO INTERSECTS PUNCTURE
  350 AOL=AP*(ZL(2)-ZP+DP)/DP
      AOG=AP-AOL
      ZLH(2)=(ZL(2)+ZP-DP)*0.5
      ZLH(4)=ZLH(3)=ZLH(2)
      PINF1=PINFG=PINF=PATM+1.DE-4*G*(ZW-0.5*(ZP+ZL(2)))/VW
      KTYP=5
      GO TO 400
C   ***
C     PUNCTURE INTERSECTS WATER LEVEL
C     CARGO BELOW PUNCTURE
  360 CONTINUE
      IF (ZL(2).GT. ZP-DP) GO TO 370
      AOG=AP
      AOL=0.
      PINF1=PINF=PATM
      A1=ZP-ZW
      A2=ZW-ZP+DP
      PINFG=(1./(A1+A2))*(A1*PATM+A2*(PATM+1.E-4*G*(ZW-ZP+DP)/2.)/VW)
      KTYP=10
      GO TO 400
C     CARGO ABOVE PUNCTURE
  370 CONTINUE
      IF(ZL(2).LT.ZP) GO TO 380
      AOL=AP
      AOG=0.
      ZLH(2)=ZP-.5*DP
      ZLH(4)=ZLH(3)=ZLH(2)
      ZLH2=(ZW+ZP-DP)*0.5
      A1=ZP-ZW
      A2=ZW-ZP+DP
      PINF1=PINFG=PINF=(1./(A1+A2))*(A1*PATM+A2*(PATM+1.E-4*
     1     G*(ZW-ZLH2)/VW))
      KTYP=3
      GO TO 400
C     CARGO INTERSECTS PUNCTURE,BUT IS ABOVE WATER
  380 CONTINUE
      IF (ZL(2).LT.ZW) GO TO 390
      AOL=AP*(ZL(2)-ZP+DP)/DP
      AOG=AP-AOL
      ZLH(2)=.5*(ZL(2)+ZP-DP)
      ZLH(4)=ZLH(3)=ZLH(2)
      A2=ZL(2)-ZW
      A3=ZW-ZP+DP
      ZLH2=0.5*(ZW+ZP-DP)
      PINFG=PATM
      PINF1=PINF=(1./(A1+A2))*(A2*PATM+1.E-4*G*(ZW-ZLH2)/VW)
      KTYP=6
      GO TO 400
C     CARGO INTERSECTS PUNCTURE,BUT IS BELOW WATER
  390 AOL=AP*(ZL(2)-ZP+DP)/DP
      AOG=AP-AOL
      ZLH(4)=ZLH(3)=ZLH(2)=(ZL(2)+ZP-DP)*.5
      A1=ZP-ZW
      A2=ZW-ZL(2)
      A3=ZL(2)-ZP+DP
```

```
      ZLH3=0.5*(ZL(2)+ZP-DP)
      PINF1=PINF=PATM+1.E-4*G*(ZW-ZLH3)/VW
      PINFG=(1./(A1+A2))*(A1*PATM+A2*(PATM+1.E-4*G*(ZW-ZL(2))*.5/VW))
      KTYP=7
C    ***
      PV(3) = CPF(1,T(3))
      L1=0
  400 CONTINUE
      PINF=PINF1
      CALL CHOKTST(KTYP,KS)
      OLDWLO=WLO
      OLDWVO=WVO
      IF(NOWVO.EQ.1.AND.PT(4).LT.PINFG) GO TO 630
      IF(NOWVO.EQ.1) GO TO 500
      GO TO (420,440),FLOSUB
  420 CALL FLOW1
      IF(INGFLG.EQ.2) CALL INGEST
      IF(INGFLG.NE.0) GO TO 610
      GO TO 500
  440 CALL FLOW2
      IF(INGFLG.EQ.2) CALL INGEST
      IF(INGFLG.NE.0) GO TO 610
  500 CONTINUE
      IF (WLO.GT.1.) GO TO 520
      DT=DMV/WVO
      DML=WLO*DT
      DMA=WAO*DT
      GO TO 530
  520 DT=DML/WLO
      DMV=WVO*DT
      DMA=WAO*DT
  530 CONTINUE
      TIME(4)=TIME(3)=TIME(2)+DT
      GO TO (540,550),ENRSUB
  540 CALL ENERGY(ITIME)
      IF(NCHANGE.EQ.2)GO TO 300
      IF(INGFLG.EQ.2) CALL INGEST
      IF(INGFLG.NE.0) GO TO 610
      GO TO 560
  550 CALL NONENER(ITIME)
      IF(INGFLG.EQ.2) CALL INGEST
      IF(INGFLG.NE.0) GO TO 610
  560 CONTINUE
      IF(ABS(OLDWLO-WLO).LE.(.001*OLDWLO).AND.
     1   ABS(OLDWVO-WVO).LE.(.001*OLDWVO)) GO TO 600
C
C     CONVERGENCE NOT ACHIEVED, SCROLL PLY 4 INTO PLY 3
      ML(3)=ML(4)
      MV(3)=MV(4)
      MA(3)=MA(4)
      ZL(3)=ZL(4)
      SVL(3)=SVL(4)
      SVV(3)=SVV(4)
      ZLH(3)=ZLH(4)
      PT(3)=PT(4)
      TIME(3)=TIME(4)
      PA(3)=PA(4)
```

```
      T(3)=T(4)
      PV(3) = PV(4)
      GO TO 400
  600 CONTINUE
      IF(NOWVO.EQ.1) WVO=WVO*((PT(4)-PINFG)/(PT(2)-PINFG))**.5
      NTEST=1
      CALL INGEST
      IF(INGFLG.EQ.0) GO TO 615
  610 IF(INGFLG.EQ.1) CALL AIRIN(ITIME)
      IF(INGFLG.EQ.3) CALL WATIN
      IF(INGFLG.EQ.4) CALL NOOUT
      IF(INGFLG.EQ.4) GO TO 615
      IF(NCHANGE.EQ.2) GO TO 500
      IF(INGFLG.EQ.1) INGFLG=0
      WRITE(NW,7200) TIME(2),ML(2),MV(2),MA(2),TML,TMV,TMA,T(2),PT(2),
     1          ZL(2)
      IF(INGFLG.EQ.0) GO TO 630
      IF(INGFLG.EQ.5) INGFLG=9
      GO TO 500
C
C     CONVERGENCE ACHIEVED ,SCROLL ALL PLYS
  615 CONTINUE
      IF(ZL(4).GT.0.0)GO TO 616
      IZERO=IZERO+1
      IF(IZERO.GT.1) GO TO 616
      TML=TML+ML(2)
      IF(HTD.EQ.-1) ENNSUB=2
      IF(HTD.EQ.-1) FLOSUB=2
      ZL(2)=0.0
      ML(2)=0.0
      ZL(4)=ZL(3)-ZL(2)
      ZLH(4)=ZLH(3)=ZLH(2)=0.0
      ML(4)=ML(3)=ML(2)
      PT(4)=PT(3)=PT(2)
      T(4)=T(3)=T(2)
      MA(4)=MA(3)=MA(2)
      MV(4)=MV(3)=MV(2)
      PV(4)=PV(3)=PV(2)
      TIME(4)=TIME(3)=TIME(2)
      ZLH(4)=ZLH(3)=ZLH(2)
      PA(4)=PA(3)=PA(2)
      SVL(4)=SVL(3)=SVL(2)
      SVV(4)=SVV(3)=SVV(2)
      CPL(4)=CPL(3)=CPL(2)
      CPVHAR(4)=CPVHAR(3)=CPVHAR(2)
      DMV=MV(2)*.01
      WRITE(12,720)
  720 FORMAT(1H ,7HRESTART)
      WRITE(NW,7200) TIME(2),ML(2),MV(2),MA(2),TML,TMV,TMA,T(2),PT(2),
     1          ZL(2)
      GO TO 500
  616 DO 620 I=2,4
      ML(I-1)=ML(I)
      MV(I-1)=MV(I)
      MA(I-1)=MA(I)
      PT(I-1)=PT(I)
      T(I-1)=T(I)
```

```
                ZL(I-1)=ZL(I)
                ZLH(I-1)=ZLH(I)
                PA(I-1)=PA(I)
                TIME(I-1)=TIME(I)
                PV(I - 1) = PV(I)
                SVL(I-1)=SVL(I)
                SVV(I-1)=SVV(I)
                CPL(I-1)=CPL(I)
                CPVBAR(I-1)=CPVBAR(I)
            620 CONTINUE
                PT(2)=PT(3)=PT(4)
                T(2)=T(3)=T(4)
                ML(2)=ML(3)=ML(4)
                MA(2)=MA(3)=MA(4)
                MV(2)=MV(3)=MV(4)
                PV(2)=PV(3)=PV(4)
                TIME(2)=TIME(3)
                ZL(2)=ZL(3)=ZL(4)
                ZLH(2)=ZLH(3)=ZLH(4)
                PA(2)=PA(3)=PA(4)
                SVL(2)=SVL(3)=SVL(4)
                SVV(2)=SVV(3)=SVV(4)
                CPL(2)=CPL(3)=CPL(4)
                CPVBAR(2)=CPVBAR(3)=CPVBAR(4)
                TML=TML+DML
                TMV=TMV+DMV
                TMA=TMA+DMA
                ITIME=ITIME+1
                WRITE(NW,7200) TIME(2),ML(2),MV(2),MA(2),TML,TMV,TMA,T(2),PT(2),
               1        ZL(2)
                IF(ABS(PT(2)-PINF+AMAX1(0.0,ZL(2)-ZP+DP)*1.0E-4*G/SVL(2))
               1      .GE.0.001*PINF) GO TO 300
            630 WRITE(NW,7280)
                WRITE(NW,7220) TIME(2),TML,TMV,TMA
          C
          C     READ FORMATS
           5000 FORMAT (A3,7X,6E10.0)
           5005 FORMAT(3E10.0,I3)
           5010 FORMAT (3E10.0)
           5020 FORMAT (1I10,6E10.0)
           5030 FORMAT(I10,7E10.0)
          C
          C     WRITE FORMATS--HEADINGS
           6000 FORMAT(1H1,////,56X,21H TANK VENTING PROGRAM  ,/,
               1        1H0,60X,11H INPUT DATA,//)
           6100 FORMAT(1H1,////,56X,21H TANK VENTING PROGRAM  ,/,
               1.       1H0,60X,7H OUTPUT ,// )
          C
          C     WRITE FORMATS
           7000 FORMAT(1H0,58X,16HCARGO PARAMETERS,//,1H0,
               1        27X,8HCARGO ID,24X,A3,5X,15HMOLECULAR WT.,7X,F15.5)
           7001 FORMAT(1H ,27X,12HINITIAL MASS,8X,E15.5,5X,12HINITIAL TEMP,8X,
               1        F15.5,/,28X,13HVOLATILE CONST,7X,F15.5)
           7010 FORMAT(1H0,59X,15HTANK PARAMETERS,//,1H0,
               1       27X,6HHEIGHT,14X,E15.5,5X,12HSURFACE AREA,8X,E15.5,/,
               2       28X,6HVOLUME,14X,E15.5,5X,8HPRESSURE,12X,F15.5,/,
               3       28X,A10,6H WALLS)
```

```
 7020 FORMAT(1H0,57X,19HPUNCTURE PARAMETERS,//,1H0,
     1       27X,11HDESCRIPTION,14X,A10,5X,/,
     2       28X,6HHEIGHT,14X,F15.5,5X,4HAREA,16X,F15.5,/,
     3       28X,10HSLOT WIDTH,10X,F15.5,5X,14HDISCHARGE COEF,6X,F15.5)
 7030 FORMAT(1H0,55X,23HSAFETY VALVE PARAMETERS,//,1H0,
     1       27X,9HCONDITION,16X,A10,5X,14HRELIEF SETTING,6X,F15.5)
 7040 FORMAT(1H0,59X,14HAIR PROPERTIES,//,1H0,
     1       27X,15HAIR TEMPERATURE,5X,F15.5,5X,12HAIR PRESSURE,8X,F15.5)
 7050 FORMAT(1H0,54X,24HCHEMICAL PROPERTIES FILE,//,1H0,
     1       27X,14HVAPOR PRESSURE,10X,3F15.5)
 7060 FORMAT(28X,14HLIQUID DENSITY,10X,2E15.5)
 7070 FORMAT(28X,21HVAPOR COMPRESSIBILITY,3X,3E15.5)
 7080 FORMAT(28X,23HSPECIFIC HEAT OF LIQUID,1X,2E15.5)
 7090 FORMAT(28X,22HSPECIFIC HEAT OF VAPOR,2X,3E15.5)
 7100 FORMAT(28X,21HLATENT HEAT OF LIQUID,3X,4E15.5,/,
     1       52X,3E15.5)
 7105 FORMAT(1H0,57X,16HWATER PARAMETERS,//)
 7110 FORMAT(1H0,27X,28HHEIGHT OF WATER OUTSIDE TANK,E15.5,5X,
     1       17HSPEC VOL OF WATER,5X,F15.5)
C     WRITE FORMATS--ERRORS
 7200 FORMAT(1H ,10E12.5)
 7220 FORMAT(7H0AT T = ,8E15.5)
 7250 FORMAT(1H1)
 7260 FORMAT(1H0,32HINITIAL PARAMETER VALUES (L,V,A),/,
     1       1H0,7HMASSES ,2X,3E15.5,/,10H SPEC VOL ,3E15.5,/,
     2       10H TL. VOL. ,3E15.5,/,10H MASS LOSS,2E15.5,/,
     3       10H LIQ LEVEL,E15.5)
 7270 FORMAT(1H0,5X,4HTIME,10X,2HML,10X,2HMV,10X,2HMA,9X,3HTML,9X,
     1                 3HTMV,9X,3HTMA,9X,4HTEMP,9X,2HPT,9X,2HZL)
 7280 FORMAT(1H0,50X,
     1       15HTOTAL MASS LOST,/,
     2       14X,4HTIME,11X,6HLIQUID,4X,5HVAPOR,
     3       12X,3HAIR)
 9000 FORMAT(27H0DATA INPUT ERROR, PINIT = ,F15.5,16HLESS THAN DPV =
     1       F15.5)
 9010 FORMAT(26H0DATA INPUT ERROR, ZL1 = ,F15.5,1X,13HGREATER THAN  ,
     1       5HZT = ,F15.5,/,10X,35HEXECUTION CONTINUING WITH ZL1=ZT =
     2     ,F15.5  )
      WRITE(NW,7285) ICT
 7285 FORMAT(1H0,/,15H ITERATIONS =  ,I5)
 4000 STOP
      END
```

```
      SUBROUTINE AIRIN(ITIME)
C     CALLED SUBROUTINES: ENERGY,ENERGY2,FLOW1,FLOW2,NONENER,NONENG2
      COMMON /GEN/ PT(4),T(4),Z'(4),ZLH(4),MA(4),MV(4),ML(4),PINF,
     1             VW,G,J,CDORF,AOL,AOG,RG1,RG,TINF,TIM(4),CMWT,
     2             VT,ZW,ZP,OPV,SVD,HTD,CPA,SVL(4),SVV(4),WLO,
     3             WVO,WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),
     4             TC,SVA,PINFG,ZT,CMI,PA(4)
      COMMON/ING/  DP,TML,TMV,TMA,DML,DMV,DMA,FLOSUB,ENRSUB,AP,INGFLG,
     1             ICT,XLP,DELTME,ZWT(4),VOLB,NTEST,NCHANGE
      COMMON/WAT/  ZLEQI,PTEQI
      INTEGER HTD,SVD,FLOSUB,ENRSUB,MA2
      REAL    ML,MV,MA,J,LAMBDA
      NW=12
      WRITE(NW,95)
   95 FORMAT(1H ,15H GOT TO AIRIN)
      PI=ACOS(-1.0)
      MA2=MA(2)
      PT2=PT(2)
      T2=T(2)
C
C     COMPUTE VOLUME OF AIR BUBBLE
C
      VOLB=PI*5.6 *4./3.*((AP/PI)**.5)**3
C
C
      KOUNT=1
   90 CONTINUE
      INGFLG=1
C
      GO TO(120,130),ENRSUB
  120 CALL ENERGY2(KOUNT)
      GO TO 140
  130 CALL NONENG2(KOUNT)
  140 CONTINUE
C
      PT(2)=PT(4)
      MA(2)=MA(4)
      T(2)=T(4)
  400 CONTINUE
      OLDWLO=WLO
      OLDWVO=WVO
      GO TO(420,440),FLOSUB
  420 CALL FLOW1
      GO TO 500
  440 CALL FLOW2
  500 CONTINUE
C     TANK PRESSURE TOO LOW...LET IN ANOTHER BUBBLE
      IF(INGFLG.EQ.2) KOUNT=KOUNT+1
      IF(INGFLG.EQ.2) GO TO 90
      IF(WLO.GT.0.0)GO TO 520
      DT=DMV/WVO
      DML=WLO*DT
      DMA=WAO*DT
      GO TO 530
  520 DT=DML/WLO
      DMV=WVO*DT
      DMA=WAO*DT
```

```
  550 CONTINUE
      TIM(4)=TIM(3)=TIM(2)+DT
      GO TO(540,550),ENRSUB
  540 CALL ENERGY(ITIME)
      GO TO 560
  550 CALL NONENER(ITIME)
  560 CONTINUE
      IF(ABS(OLDWLO-WLO).LE.(.001*OLDWLO).AND.
     1   ABS(OLDWVO-WVO).LE.(.001*OLDWVO)) GO TO 600
C
C     CONVERGENCE NOT ACHIEVED,SCROLL
      ML(3)=ML(4)
      MV(3)=MV(4)
      MA(3)=MA(4)
      ZL(3)=ZL(4)
      SVL(3)=SVL(4)
      SVV(3)=SVV(4)
      ZLH(3)=ZLH(4)
      PT(3)=PT(4)
      TIM(3)=TIM(4)
      PA(3)=PA(4)
      T(3)=T(4)
      PV(3)=PV(4)
      WRITE(NW,7290) ML(3),MV(3),MA(3),ZL(3),PT(3),T(3),PV(3)
 7290 FORMAT(6H NC***,7E12.5,4H ***)
      GO TO 400
  600 CONTINUE
C
C     CONVERGENCE ACHIEVED, NEW PT(4) FOUND
C     TEST PT(4) FOR CONVERGENCE
      A1=(PT(4)+(.0001*G/SVL(4))*(ZL(4)-ZP))/(PT2+(.0001*G/SVL(2))*
     1   (ZL(2)-ZP))
      IF(A1.GE..95.AND.A1.LE.1.05) GO TO 700
C
C     DML NOT CORRECT FOR PT(4).
C     MODIFY DML AND TRY AGAIN
C
      TN=0.0
      DML=DML*(TN+A1)/(TN+1.0)
      GO TO 400
  700 CONTINUE
C
C     CHECK FOR LIQUID LEVEL EQUAL TO TOP OF PUNCTURE
C
      IF(ZL(4).LE.ZP) GO TO 720
C
C     SCROLL AND ADD ALL RISE TIMES TO TIME STEP
      DO 710 I=2,4
      ML(I-1)=ML(I)
      MV(I-1)=MV(I)
      MA(I-1)=MA(I)
      PT(I-1)=PT(I)
      T(I-1)=T(I)
      ZL(I-1)=ZL(I)
      ZLH(I-1)=ZLH(I)
      PA(I-1)=PA(I)
      TIM(I-1)=TIM(I)
```

```
      PV(I-1)=PV(I)
      SVL(I-1)=SVL(I)
      SVV(I-1)=SVV(I)
      CPL(I-1)=CPL(I)
      CPVBAR(I-1)=CPVBAR(I)
  710 CONTINUE
      PT(2)=PT(3)=PT(4)
      T(2)=T(3)=T(4)
      ML(2)=ML(3)=ML(4)
      MA(2)=MA(3)=MA(4)
      MV(2)=MV(3)=MV(4)
      PV(2)=PV(3)=PV(4)
      TIM(2)=TIM(3)=TIM(4)
      ZL(2)=ZL(3)=ZL(4)
      ZLH(2)=ZLH(3)=ZLH(4)
      PA(2)=PA(3)=PA(4)
      SVL(2)=SVL(3)=SVL(4)
      SVV(2)=SVV(3)=SVV(4)
      CPL(2)=CPL(3)=CPL(4)
      CPVBAR(2)=CPVBAR(3)=CPVBAR(4)
      TML=TML+DML
      TMV=TMV+DMV
      TMA=TMA+DMA
      WRITE(NW,7200) TIM(2),ML(2),MV(2),MA(2),TML,TMV,TMA,T(2),PT(2),
     1     ZL(2)
 7200 FORMAT(1H ,10E12.5)
      GO TO 90
  720 CONTINUE
      PT(2)=PT(1)
      MA(2)=MA(1)
      T(2)=T(1)
      RETURN
      END
```

```
SUBROUTINE AIRMASS     76/74    OPT=1                         FTN 4.6+433F        80/08/15. 13.45.07        PAGE     1

              SUBROUTINE AIRMASS
        C
        C     CALCULATES MASS OF THE AIR FOR ITERATION IN INGEST
        C     CALLED FUNCTIONS: CPF
        C
              COMMON /GEN/ PT(4),T(4),ZL(4),ZLH(4),MA(4),MV(4),ML(4),PINF,
             1             VW,G,J,CDORF,AOL,AOG,RG1,RG,TATM,TIN(4),MOLE,
             2             VOLT,ZW,ZP,DELPVAL,IVALVE,IHEATTR,CPA,VL(4),VV(4),
             3             WLO,WVO,WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),
             4             TC,SVA,PINFG,ZT,CMI,PA(4)
              REAL MA,MV,ML,MOLE,J,LAMBDA
        C
              ZL(4)=(ML(4)*(1./CPF(2,T(4))))/AT
              VOLG=VOLT- ZL(4)*AT
              MA(4)=(28.96*(PT(4)-PV(4))*VOLG)/((T(4)+273.2)*RG)
              RETURN
              END
```

```
      SUBROUTINE CHOKTST(KTYP,K5)
C     CALLED FUNCTIONS: CPF,CPLHF,GAMM
      COMMON /GEN/PT(4),T(4),ZL(4),ZLH(4),MA(4),MV(4),ML(4),PINF,
     1             VW,G,J,COORF,AOL,AOG,RG1,RG,TINF,TIM(4),CMWT,
     2             VT,ZW,ZP,DPV,SVD,HTD,CPA,SVL(4),SVV(4),WLO,
     3             WVO,WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),
     4             TC,SVA,PINFG,ZT,CMI,PA(4)
      COMMON/ING/ DP,TML,TMV,TMA,DML,DMV,DMA,FLOSUB,ENRSUB,AP,INGFLG,
     1             ICT,XLP,DELTME,ZWT(4),VOLB,NTEST,NCHANGE
      COMMON/WAT/ /LEQI,PTEQI
      COMMON/CP/  A,B,C,DA,DB,ZA,ZB,ZC,CA,CB,VA,VB,VC,
     1             HA,HB,HC,HD,HE,HF,TA
      INTEGER HTD,SVD,FLOSUB,ENRSUB
      REAL    ML,MV,MA,J,LAMBDA,LAM01,LAM02,LAMBAR
      AVERAGE(X)=(X(2)+X(4))/2.0
      IF(K5.GT.1) RETURN
C     DO NOT CHECK CHOKTST
      IF(PT(2).LE.1.05*PINF) GO TO 675
C
C     ESTABLISH KTYPS THAT REPRESENT LIQUID AND VAPOR FLOWS
      ILIQ=IGAS=ILAG=0
      IK=0
      IF(KTYP.EQ.1.OR.KTYP.EQ.2.OR.KTYP.EQ.3) ILIQ=1
      IF(KTYP.EQ.3.OR.KTYP.EQ.9.OR.KTYP.EQ.10) IGAS=1
      IF(KTYP.EQ.4.OR.KTYP.EQ.5.OR.KTYP.EQ.6.OR.KTYP.EQ.7)ILAG=1
C
C     GO TO 500 IF ONLY LIQUID ESCAPES
C
      IF(ILIQ.EQ.1.AND.IGAS.EQ.0) GO TO 500
C
C     GO TO 600 IF ONLY VAPOR ESCAPES
C
      IF(ILIQ.EQ.0.AND.IGAS.EQ.1) GO TO 600
C
C     LIQUID AND GAS ESCAPES
C     TEST IF NONENER AND FLOW2 ARE BEING USED
      IF(FLOSUB.EQ.2) GO TO 600
C
C     ENERGY AND FLOW1 ARE BEING USED
C
      IK=1
      GO TO 505
C     CASE 2.A
  500 IF(FLOSUB.EQ.2)GO TO 675
C
C     CASE 1.A
  505 ICTT=0
      T01=CPF(6,PINF)
      T02=(T(2)+T01)*.5
  550 CPLT01=CPF(4,(T(2)+T01)*.5)
      CPLT02=CPF(4,(T(2)+T02)*.5)
      SVV(4)=CPF(3,T(2))*RG*(T(2)+273.2)/(CMWT*PV(2))
      SVL(4)=1./CPF(2,T(2))
      LAM01=CPLHF(T01)
      LAM02=CPLHF(T02)
      X01=CPLT01*(T01+273.2)*(ALOG((T(2)+273.2)/(T01+273.2)))/LAM01
      X02=CPLT02*(T02+273.2)*(ALOG((T(2)+273.2)/(T02+273.2)))/LAM02
```

```
      P01=CPF(1,T01)
      P02=CPF(1,T02)
      VV01=CPF(3,T01)*RG*(T01+273.2)/(CMWT*P01)
      VV02=CPF(3,T02)*RG*(T02+273.2)/(CMWT*P02)
      VL01=1./CPF(2,T01)
      VL02=1./CPF(2,T02)
      LAMBAR=(LAM01+LAM02)/2.
      DERIV1=((CPLT02*(T(2)-T02)-X02*LAM02)-(CPLT01*(T(2)-T01)-
     1       X01*LAM01))/(T02-T01)
      DERIV2=(.12*X02*VV02-.12*X01*VV01+VL02*(1.-.12*X02)-
     1     VL01*(1.-.12*X01))/(T02-T01)
      DER=DERIV1/DERIV2
      CPLAVG=(CPLT01+CPLT02)*.5
      CONST=B*(T(2)+273.2)*ALOG(10.)/(C+T(2))**2 - 1.5
      DELT=(T(2)+273.2)*(.12*SVV(2)*DER/LAMBAR +
     1     ((.12*SVV(2)/LAMBAR)**2*DER**2 +6.*SVL(2)*DER*
     2     (1.-.12*SVV(2)*DER*CONST/LAMBAR)/(CPLAVG*T(2))))**.5/
     3     ((1.-.12*SVV(2)*DER*CONST/LAMBAR)*2.)
      T01=T(2)-DELT
      T02=T01-2.*(T(2)-T01)/5.
      ICTT=ICTT+1
      IF(ICTT.EQ.1) GO TO 350
      PO=CPF(1,T01)
      IF(PO.LE.PINF.AND.IK.EQ.1) GO TO 600
      IF(PO.LE.PINF) GO TO 675
      IF(PO.GT.PINF) GO TO 300
  350 CONTINUE
      IF(PO.GT.PINF) PINF=PO
      IF(IK.EQ.1) GO TO 600
      GO TO 674
  300 CONTINUE
      GO TO 350
C
C     CASE 1.B (USES FLOW1) AND 2.B (USES FLOW2)
C     ONLY VAPOR CAN ESCAPE
C
  600 RV1=RG1/CMWT
      GAMMAN=GAMM(RA)
      PO=PT(2)*(2./(GAMMAN+1.))**(GAMMAN/(GAMMAN-1.))
      TO=(T(2)+273.2)*(PO/PT(2))**((GAMMAN-1.)/GAMMAN)-273.2
      CPVAVE=(CPF(5,T(2))+ CPF(5,TO))*.5
      GAMMAN=CPVAVE/(CPVAVE-RV1)
      PO=PT(2)*(2./(GAMMAN+1.))**(GAMMAN/(GAMMAN-1.))
      IF(PO.LE.PINFG) GO TO 675
      PINFG=PO
  674 K5=1
      RETURN
  675 K5=2
      RETURN
      END
```

```
SUBROUTINE CORRECT    76/74   OPT=1                    FTN 4.6+433F      80/08/15. 13.45.07      PAGE    1

            SUBROUTINE CORRECT
      C
      C     CALCULATES CORRECTED VALUES IN ENERGY
      C     CALLED FUNCTIONS: CPF,CPLHF
      C
            COMMON /GEN/ PT(4),T(4),ZL(4),ZLH(4),MA(4),MV(4),ML(4),PINF,
           1             VW,G,J,CDORF,AOL,AOG,RG1,RG,TATM,TIM(4),MOLE,
           2             VOLT,ZW,ZP,DELPVAL,IVALVE,IHEATTR,CPA,VL(4),VV(4),
           3             WLO,WVO,WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),
           4             TC,SVA,PINFG,ZI,CHI,PA(4)
            REAL MA,MV,ML,MOLE,LAMBDA,J
            PT(3)=PT(4)
            PV(3)=PV(4)
            LAMBDA(3)=LAMBDA(4)
            LAMBDA(4)=CPLHF(T(4))
            ML(3)=ML(4)
            MV(3)=MV(4)
            VV(3)=VV(4)
            VV(4)=CPF(3,T(4))*(RG/MOLE)*(T(4)+273.2)/CPF(1,T(4))
            VL(3)=VL(4)
            VL(4)=1./CPF(2,T(4))
            CPL(3)=CPL(4)
            CPL(4)=CPF(4,T(4))
            CPVBAR(3)=CPVBAR(4)
            CPVBAR(4)=CPF(5,T(4))
            RETURN
            END
```

```
FUNCTION CPF        74/74    OPT=1                          FTN 4.6+433F       80/08/15. 13.45.07       PAGE     1

                FUNCTION CPF(IFLAG,T)
                COMMON /CP/ PA,PB,PT,DA,DB,ZA,ZB,ZC,CA,CB,VA,VB,VC,
               1             HA,HB,HC,HD,HE,HF,TA
          C
          C     CHEMICAL PROPERTIES FILE FUNCTION SUBPROGRAM
          C     NOTE: ALL TEMPERATURES ARE IN DEG C
          C
                GO TO (100,200,300,400,500,600),IFLAG
          C
          C     VAPOR PRESSURE VS TEMPERATURE, IFLAG=1
            100 CPF=10.**(PA-PB/(T+PT))
                RETURN
          C
          C     LIQUID DENSITY, IFLAG=2
            200 CPF=DA-DB*T
                RETURN
          C
          C     VAPOR COMPRESSIBILITY, IFLAG=3
            300 CPF=ZA-ZB*T-ZC*T**2
                RETURN
          C
          C     SPECIFIC HEAT OF CARGO,IFLAG=4
            400 CPF=CA+CB*T
                RETURN
          C
          C     SPECIFIC HEAT OF VAPOR, IFLAG=5
            500 CPF=VA-VB*T-VC*T**2
                RETURN
          C
          C     TEMPERATURE DETERMINED FROM VAPOR PRESSURE, IFLAG=6
            600 CPF=-1.*(PT + PB/(ALOG10(T)-PA))
                RETURN
          C
                END
```

```
FUNCTION CPLHF        76/74    OPT=1                        FTN 4.6+435F        80/08/15. 13.45.07        PAGE     1

              FUNCTION CPLHF(T)
        C     CALLED FUNCTIONS: CPF
              COMMON /CP/ PA,PB,PT,DA,DB,ZA,ZB,ZT,CA,CB,VA,VB,VC,
             1            HA,HB,HC,HD,HE,HF,TA
        C
        C     CALCULATES THE LATENT HEAT OF THE CARGO
              C1=(HA-HB*T-HC*T**2)*((T+273.2)/(T+TA))**2
              C2=HD*CPF(1,1)*(T+273.2)
              C3=(T+TA)**2 * (HE-HF*T)
              CPLHF=C1 - C2/C3
              RETURN
              END
```

```
      SUBROUTINE ENERGY(ITIME)
C
C     DETERMINES PRESSURE AND TEMPERATURE OF THE TANK CARGO
C     AS LIQUID OR VAPOR IS VENTED
C
C     CALLED SUBROUTINES: CORRECT,FLOW1,TERMIN,ZLHCALC
C     CALLED FUNCTIONS: CPF,CPLHF
      REAL LAMBDA,MA,ML,MV,MACPAV,MLCPLAV,MVCPVBA,J,
     1                MOLE
      COMMON /GEN/ PT(4),T(4),ZL(4),ZLH(4),MA(4),MV(4),ML(4),PINF,
     1                VW,G,J,CDORF,AOL,AOG,RG1,RG,IATM,TIM(4),MOLE,
     2                VOLT,ZW,ZP,DELPVAL,IVALVE,IHEATTR,CPA,VL(4),VV(4),
     3                WLO,WVO,WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),
     4                TC,SVA,PINFG,ZT,CMI,PA(4)
      COMMON/ING/  DP,IML,IMV,IMA,DML,DMV,DMA,FLOSUO,ENHSUB,AP,INGFLG,
     1               ICT,XLP,DELTME,ZUT(4),VOLB,NTEST,NCHANGE
      COMMON /WNAME/ NUWVO
      AVERAGE(X)=(X(4)+X(2))/2.0
      LAMBDA(1)=LAMBDA(2)=CPLHF(T(2))
C     GUESS CONDITIONS OF NEXT TIME STEP
C
      PT(4)=PT(3)-PT(2)
      T(4)=T(3)=T(2)
      LAMBDA(4)=LAMBDA(3)=LAMBDA(2)
      VVTWO=CPF(3,T(2))*(RG/MOLE)*(T(2)+273.2)/CPF(1,T(2))
      VV(4)=VV(3)=CPF(3,T(3))*(RG/MOLE)*(T(3)+273.2)/CPF(1,T(3))
      VL(4)=VL(3)-1./CPF(2,T(3))
      DELTME=(((VV(4)+VVTWO)*.5*WVO+AVERAGE(VL)*WLO)*(TIM(3)-TIM(2))-
     1     AVERAGE(MV)*(VV(4)-VVTWO)-AVERAGE(ML)*(VL(4)-VL(2)))/
     2     ((VV(4)+VVTWO)*.5-AVERAGE(VL))
      ML(4)=ML(2)-WLO*(TIM(3)-TIM(2))-DELTME
      MV(4)-MV(2)+DELTME-WVO*(TIM(3)-TIM(2))
      CPL(4)=CPL(3)=CPF(4,T(3))
      CPVBAR(4)=CPVBAR(3)=CPF(5,T(3))
      IF(WLO.GT.0.0) GO TO 60
      DT=DMV/WVO
      DML=WLO*DT
      DMA=WAO*DT
      GO TO 65
   60 DT=DML/WLO
      DMV=WVO*DT
      DMA=WAO*DT
   65 CONTINUE
C
C     IS VALVE UNSTUCK?
C
      IF(IVALVL.EQ.1)GO TO 500
C
C     RELIEF VALVE STUCK
C     IS TANK LIQUID LEVEL AT LEAST PARTIALLY BELOW PUNCTURE
C
      IF((ZL(4)-ZP+DP).LE.0.0.AND.PT(4).LE.PINF)
     1     CALL TERMIN(10H MAIN      )
      IF(ZL(4).LE.ZP)GO TO 400
C
C     ADIABATIC PROCESS- PUNCTURE BELOW TANK LIQUID LEVEL
C
```

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          WA=WAO=WVO=0.0
    105   MACPAV=((MA(2)*CPA)+ (MA(4)*CPA))/2.0
          MLCPLAV=((ML(2)*CPL(2))+(ML(4)*CPL(4)))/2.0
          MVCPVBA=((MV(2)*CPVBAR(2)) + (MV(4)*CPVBAR(4)))/2.0
          OLDWLO=WLO
          NCHANGE=1
C
C         SECTION   1.1   PUNCTURE BELOW TANK LIQUID LEVEL
C         CHECK FOR ISOTHERMAL OPTION
C
          IF(IHEATIR.EQ.-1) T(4)=T(2)
          IF(IHEATIR.EQ.-1) GO TO 120
          VV(4)=CPF(3,T(4))*(RG/MOLE)*(T(4)+273.2)/CPF(1,T(4))
          DELTME=(((VV(4)+VVTWO)*.5*WVO+AVERAGE(VL)*WLO)*(TIM(3)-TIM(2))-
     1         AVERAGL(MV)*(VV(4)-VVTWO)-AVERAGE(ML)*(VL(4)-VL(2)))/
     2         ((VV(4)+VVTWO)*.5-AVERAGE(VL))
          IF(ZL(2).EQ.0.0) GO TO 106
          DELTME=DELTME-1.9/(AT*100.*(RG*(AVERAGE(T)+273.2)/MOLE)**.5/
     1         AVERAGE(VL))**.25*(DELTME/DT)**1.25*DT
    106   VV(4)=2.*(AVERAGE(VL)*DELTME*AVERAGE(VL)*WLO*DT+2.*AVERAGE(MV)
     1         *VV(2)-AVERAGE(ML)*(VL(4)-VL(2)))/(DELTME-WVO*DT+
     2         2.*AVERAGE(MV))-VV(2)
          PV(4)=CPF(3,T(4))*RG*(T(4)+273.2)/(MOLE*VV(4))
          PA(4)=(MA(4)*RG/28.96*(T(4)+273.2))/(VOLT-ML(4)*VL(4))
          PT(4)=PV(4)+PA(4)
    110   T(4)=((VOLT*(PT(4)-PT(2))*10000.)/J+AVERAGE(LAMBDA)*(ML(4)-ML(2))+
     1         AVERAGE(LAMBDA)*WLO*DT+WA*CPA*(TATM-
     2         AVERAGE(T))*DT)/(MLCPLAV+MVCPVBA+MACPAV)+T(2)
C
C         CALCULATE CORRECTED VALUES
C
          VV4=VV(4)
          CALL CORRECJ
          VV(4)=VV4
    120   CALL FLOW1
          IF(INGFLG.EQ.2) RETURN
          IF(WLO.GT.0.0) GO TO 130
          DT=DMV/WVO
          DML=WLO*DT
          DMA=WAO*DT
          GO TO 135
    130   DT=DML/WLO
          DMV=WVO*DT
          DMA=WAO*DT
    135   CONTINUE
          ML(4)=ML(2)-WLO*DT-DELTME
          MV(4)=MV(2)+DELTME
          ZL(4)=ML(4)*VL(4)/AT
          IF(ZL(4).LE.ZP) GO TO 400
          CALL ZLHCALC
C
C         CHECK FOR CONVERGENCE
C
          IF(ABS(WLO-OLDWLO).LE.(.001*OLDWLO)) GO TO 1000
          ZL(3)=ZL(4)
          ZLH(3)=ZLH(4)
          PA(3)=PA(4)
```

```
          T(3)=T(4)
          GO TO 105
  400     CONTINUE
          IF(NCHANGE.EQ.1) CALL SCROLL
          IF(NCHANGE.EQ.1)NCHANGE=NCHANGE+1
          IF(NCHANGE.EQ.2)RETURN
C
C         SECTION 1.2 TANK LIQUID LEVEL IS AT LEAST PARTIALLY BELOW PUNCTURE
C                     AND PT.GT.PATM
C
          IF(PT(4).LE.PATM) GO TO 450
          WA=WAO=0.0
  405     MLCPLAV=((ML(2)*CPL(2))+(ML(4)*CPL(4)))/2.0
          MACPAV=((MA(2)*CPA)+(MA(4)*CPA))/2.0
          MVCPVBA=((MV(2)*CPVBAR(2))+(MV(4)*CPVBAR(4)))/2.0
          OLDWVO=WVO
C
C         CHECK FOR ISOTHERMAL OPTION
C
          IF(IHEATTR.EQ.-1)T(4)=T(2)
          IF(IHEATTR.EQ.-1) GO TO 420
          VV(4)=CPF(3,T(4))*(RG/MOLE)*(T(4)+273.2)/CPF(1,T(4))
          DELTME=(((VV(4)+VVTWO)*.5*WVO+AVERAGE(VL)*WLO)*(TIM(3)-TIM(2))-
         1       AVERAGE(MV)*(VV(4)-VVTWO)-AVERAGE(ML)*(VL(4)-VL(2)))/
         2       ((VV(4)+VVTWO)*.5-AVERAGE(VL))
          IF(DELTME.LT.0.0) GO TO 1000
          IF(ZL(2).EQ.0.0) GO TO 406
          DELTME=DELTME-1.9/(AT*100.*(RG*(AVERAGE(T)+273.2)/MOLE)**.5/
         1       AVERAGE(VL))**.25*(DELTME/DT)**1.25*DT
  406     MV(4)=MV(2)-WVO*DT+DELTME
          ML(4)=ML(2)-WLO*DT-DELTME
          IF(ML(4).LT.0.0) GO TO 1000
          VV(4)=2.*(AVERAGE(VL)*DELTME+AVERAGE(VL)*WLO*DT+2.*AVERAGE(MV)
         1       *VV(2)-AVERAGE(ML)*(VL(4)-VL(2)))/(DELTME-WVO*DT+
         2       2.*AVERAGE(MV))-VV(2)
          PV(4)=CPF(3,T(4))*RG*(T(4)+273.2)/(MOLE*VV(4))
          PA(4)=(MA(4)*RG/28.96*(T(4)+273.2))/(VOLT-ML(4)*VL(4))
          PT(4)=PV(4)+PA(4)
          T(4)=((VOLT*(PT(4)-PT(2))*10000.)/J+AVERAGE(LAMBDA)*(ML(4)-ML(2))+
         1       AVERAGE(LAMBDA)*WLO*DT+WA*CPA*(TATM-
         2       AVERAGE(T))*DT)/(MLCPLAV+MVCPVBA+MACPAV)+T(2)
C
C         CALCULATE CORRECTED VALUES
C
          VV4=VV(4)
          CALL CORRECT
          VV(4)=VV4
          IF(ABS(PT(4)-PINFG).LT..005*PINFG) NOWVO=1
          IF(ABS(PT(4)-PINFG).LT..005*PINFG) GO TO 450
  420     CALL FLOW1
          IF(INGFLG.EQ.2) RETURN
          GO TO 442
  450     CONTINUE
  442     CONTINUE
          IF(WLO.GT.0.0) GO TO 435
          DT=DMV/WVO
          DML=WLO*DT
```

```
      DMA=WAO*DT
      GO TO 440
  435 DT=DML/WLO
      DMV=WVO*DT
      DMA=WAO*DT
  440 CONTINUE
      MV(4)=MV(2)-WVO*DT+DELTME
      ML(4)=ML(2)-WLO*DT-DELTME
      IF(ML(4).LT.0.0) GO TO 1000
      ZL(4)=ML(4)*VL(4)/AT
      CALL ZLHCALC
C
C     CHECK FOR CONVERGENCE
C
      IF(ABS(WVO-OLDWVO).LE.(.001*OLDWVO)) GO TO 1000
      ZL(3)=ZL(4)
      T(3)=T(4)
      PA(3)=PA(4)
      ZLH(3)=ZLH(4)
      GO TO 405
  450 CONTINUE
C
C     SECTION 1.3 TANK LIQUID LEVEL IS AT LEAST PARTIALLY BELOW PUNCTURE AND
C     PT.EQ.PATM
C
      IF(PT(4).LT.PATM) PT(4)=PATM
      WAO=WVO-0.0
  455 MLCPLAV=((ML(2)*CPL(2))+(ML(4)*CPL(4)))/2.0
      MACPAV=((MA(2)*CPA)+(MA(4)*CPA))/2.0
      MVCPVBA=((MV(2)*CPVBAR(2))+(MV(4)*CPVBAR(4)))/2.0
      OLDWLO=WLO
C
C     CHECK FOR ISOTHERMAL OPTION
C
      IF(IHEATTR.EQ.-1)T(4)=T(2)
      IF(IHEATTR.EQ.-1)GO TO 470
      VV(4)=CPF(3,T(4))*(RG/MOLE)*(T(4)+273.2)/CPF(1,T(4))
      DELTME=(((VV(4)+VVTWO)*.5*WVO*AVERAGE(VL)*WLO)*(TIM(3)-TIM(2))-
     1      AVERAGE(MV)*(VV(4)-VVTWO)-AVERAGE(ML)*(VL(4)-VL(2)))/
     2      ((VV(4)+VVTWO)*.5-AVERAGE(VL))
      IF(ZL(2).EQ.0.0) GO TO 456
      DELTME=DELTME-1.9/(AT*100.*(RG*(AVERAGE(T)+273.2)/MOLE)**.5/
     1      AVERAGE(VL))**.25*(DELTME/DT)**1.25*DT
  456 VV(4)=2.*(AVERAGE(VL)*DELTME+AVERAGE(VL)*WLO*DT+2.*AVERAGE(MV)
     1      *VV(2)-AVERAGE(ML)*(VL(4)-VL(2)))/(DELTME-WVO*DT+
     2      2.*AVERAGE(MV))-VV(2)
      PV(4)=CPF(3,T(4))*RG*(T(4)+273.2)/(MOLE*VV(4))
      PT(4)=PATM
      T(4)=((VOLT*(PT(4)-PT(2))*10000.)/J+AVERAGE(LAMBDA)*(ML(4)-ML(2))+
     1      AVERAGE(LAMBDA)*WLO*DT+WA*CPA*(TATM-
     2      AVERAGE(T))*DT)/(MLCPLAV+MVCPVBA+MACPAV)+T(2)
C
C     CALCULATE CORRECTED VALUES
C
      VV4=VV(4)
      CALL CORRECT
      VV(4)=VV4
```

```
  470 CALL FLOUT
      IF(INGFLG.EQ.2) RETURN
      IF(WLO.GT.0.0) GO TO 485
      DT=DMV/WVO
      DML=WLO*DT
      DMA=WAO*DT
      GO TO 490
  485 DT=DML/WLO
      DMV=WVO*DT
      DMA=WAO*DT
  490 CONTINUE
      ML(4)=ML(2)-WLO*DT-DELTME
      MV(4)=MV(2)+DELTME
      MA(4)=((PATM-PV(4))*(VOLT-ML(4)*(1./CPF(2,T(4)))))/
     1      (RG*(T(4)+273.2)/28.96)
      WA=(MA(4)-MA(2))/DT
      ZL(4)=ML(4)*VL(4)/AT
      CALL ZLHCALC
      T(3)=T(4)
C
C     CHECK FOR CONVERGENCE
C
      IF(ABS(WLO-OLDWLO).LE.(.001*OLDWLO)) GO TO 1000
      ZLH(3)=ZLH(4)
      GO TO 455
  500 CONTINUE
C
C*****RELIEF VALVE UNSTUCK*****
C
C     SECTION II.1 TANK LIQUID LEVEL IS ABOVE PUNCTURE AND
C                  PT .GT. PATM-DELPVAL
C
      IF(ZL(4).GT.ZP.AND.PT(4).GT.(PATM-DELPVAL))GO TO 105
C
C     SECTION II.2 TANK LIQUID LEVEL IS ABOVE PUNCTURE AND
C                  PT .LE. PATM-DELPVAL
C
      IF(ZL(4).GT.ZP.AND.PT(4).LE.(PATM-DELPVAL)) GO TO 515
      GO TO 600
  515 IF(PT(4).LT.(PATM-DELPVAL)) PT(4)=PATM-DELPVAL
      MACPAV=((MA(2)*CPA)+(MA(4)*CPA))/2.0
      MLCPLAV=((ML(2)*CPL(2))+(ML(4)*CPL(4)))/2.0
      MVCPVDA=((MV(2)*CPVDAR(2))+(MV(4)*CPVDAR(4)))/2.0
      OLDWLO=WLO
C
C     CHECK FOR ISOTHERMAL OPTION
C
      IF(IHEATIN.EQ.-1)T(4)=T(3)
      IF(IHEATIN.EQ.-1)GO TO 520
      VV(4)=CPF(3,T(4))*(RG/MOLE)*(T(4)+273.2)/CPF(1,T(4))
      DELTME=(((VV(4)+VVTWO)*.5*WVO+AVERAGE(VL)*WLO)*(TIN(3)-TIN(2))-
     1      AVERAGE(MV)*(VV(4)-VVTWO)-AVERAGE(ML)*(VL(4)-VL(2)))/
     2      ((VV(4)+VVTWO)*.5-AVERAGE(VL))
      IF(ZL(2).EQ.0.0) GO TO 516
      DELTME=DELTME-1.9/(AT*100.*(RG*(AVERAGE(T)+273.2)/MOLE)**.5/
     1      AVERAGE(VL))**.25*(DELTME/DT)**1.25*DT
  516 VV(4)=2.*(AVERAGE(VL)*DELTME+AVERAGE(VL)*WLO*DT+2.*AVERAGE(MV)
```

```
     1      *VV(2)-AVERAGE(ML)*(VL(4)-VL(2)))/(DELTME-WVO*DT*
     2      2.*AVERAGE(MV))-VV(2)
      PV(4)=CPF(3,T(4))*RG*(T(3)+273.2)/(MOLE*VV(3))
      PT(4)=PT(3)=PATM-DELPVAL
      T(4)=((VOLT*(PT(4)-PT(2))*10000./J+AVERAGE(LAMBDA)*(ML(4)-ML(2))+
     1      AVERAGE(LAMBDA)*WLO*DT+WA*CPA*(TATM-
     2      AVERAGE(T))*DT)/(MLCPLAV+MVCPVBA+MACPAV)+T(2)
C
C     CALCULATE CORRECTED VALUES
C
      VV4=VV(4)
      CALL CORRECT
      VV(4)=VV4
  520 CALL FLOWS
      IF(ENGFLG.EQ.2) RETURN
      IF(WLO.GT.0.0) GO TO 530
      DT=DMV/WVO
      DML=WLO*DT
      DMA=WAO*DT
      GO TO 535
  530 DT=DML/WLO
      DMV=WVO*DT
      DMA=WAO*DT
  535 CONTINUE
      ML(4)=ML(2)-WLO*DT-DELTME
      MV(4)=MV(2)+DELTME
      MA(4)=(PATM-DELPVAL-PV(4))*(VOLT-ML(4)*(1./CPF(2,T(4))))/
     1      (RG*(T(4)+273.2)/28.96)
      WA=(MA(4)-MA(2))/DT
      ZL(4)=ML(4)*VL(4)/AT
      CALL ZLHCALC
C
C     CHECK FOR CONVERGENCE
C
      IF(ABS(WLO-OLDWLO).LE.(.001*OLDWLO)) GO TO 1000
      T(3)=T(4)
      ZLH(3)=ZLH(4)
      GO TO 515
C
C     SECTION II.3 TANK LIQUID LEVEL IS PARTIALLY BELOW PUNCTURE AND
C                  PT .GT. PATM
C
  600 WA=WAO=0.0
      IF((ZL(4)-ZP+DP).LE.0.0.AND.WVO.LE.0.0) CALL TERMIN(10H MAIN     )
      IF(PT(4).GT.PATM) GO TO 405
C
C     SECTION II.4 TANK LIQUID LEVEL IS PARTIALLY BELOW PUNCTURE AND
C                  PT=PATM-DELPVAL
      IF(PT(4).LE.(PATM-DELPVAL)) PT(4)=PATM
      IF(ITIME.NE.1)WAO=WVO=0.0
      IF(ITIME.NE.1) GO TO 455
      PT(2)=PATM-DELPVAL
      PT(4)=PATM
      PV(4)=CPF(2,T(4))
      MA(4)=(PATM-PV(4))*(VOLT-ML(4)*(1./CPF(2,T(4))))/
     1      (RG*(T(4)+273.2)/28.96)
      WA=(MA(4)-MA(2))/DT
```

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                 WAO=WVO=0.0
            700  WRITE(12,710) PT(3),PT(4),PATM,ZL(3),ZL(4),ZP
            710  FORMAT(1H ,25HERROR IN CHECK STATEMENTS,/,
                1   8H PT(3)= ,F15.5,8H PT(4)= ,F15.5,7H PATM= ,F15.5,/,
                2   8H ZL(3)= ,F15.5,8H ZL(4)= ,F15.5,5H ZP= ,F15.5)
           C     CONVERGENCE ACHIEVED
           1000  CONTINUE
                 RETURN
                 END
```

```
            SUBROUTINE ENERGY2(KOUNT)
      C     CALLED SUBROUTINES: CORRECT,ZLHCALC
      C     CALLED FUNCTIONS: CPF,CPLHF
            REAL LAMBDA,MA,ML,MV,MACPAV,MLCPLAV,MVCPVBA,J,
           1             MOLE
            COMMON /GEN/ PT(4),T(4),ZL(4),ZLH(4),MA(4),MV(4),ML(4),PINF,
                         VW,G,J,CDORF,AOL,ADG,RG1,RG,TATM,TTM(4),MOLE,
           1             VOLT,ZW,ZP,DELPVAL,IVALVE,IHEATTR,CPA,VL(4),VV(4),
           2             WLO,WVO,WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),
           3             TC,SVA,PINFG,ZT,CMI,PA(4)
           4
            COMMON/ING/  DP,TML,TMV,TMA,DML,DMV,DMA,FLOSUB,ENRSUB,AP,INGFLG,
           1             ICT,XLP,DELTME,ZWT(4),VOLB,NTEST,NCHANGE
            AVERAGE(X)=(X(2)+X(4))/2.0
            WRITE(12,50)
         50 FORMAT(1H ,14HGOT TO ENERGY2)
            NW=12
            RA=RG/28.96
            PT(3)=PT(4)
            T(3)=T(4)
            LAMBDA(4)=LAMBDA(3)=CPLHF(T(3))
            VV(4)= VV(3)=CPF(3,T(3))+(RG/MOLE)*(T(3)+273.2)/CPF(1,T(3))
            VL(4)=VL(3)=1./CPF(2,T(3))
            WLO=WAO=WVO=0.0
            CPVBAR(4)=CPVBAR(3)=CPF(5,T(3))
            CPL(4)=CPL(3)=CPF(4,T(3))
        105 MACPAV=((MA(2)*CPA)+(MA(4)*CPA))/2.0
            MVCPVBA=((MV(2)*CPVBAR(2))+(MV(4)*CPVBAR(4)))/2.0
            MLCPLAV=((ML(2)*CPL(2))+(ML(4)*CPL(4)))/2.0
      C
      C     PUNCTURE BELOW TANK LIQUID LEVEL
      C     CHECK FOR ISOTHERMAL OPTION
      C
            IF(IHEATTR.EQ.-1)T(4)=T(2)
            IF(IHEATTR.EQ.-1)GO TO 120
            T(3)=T(4)
            ML(4)=ML(2)
            MV(4)=MV(2)
        110 T(4)=((VOLT*(PT(4)-PT(2))*10000.)/J+AVERAGE(LAMBDA)*(ML(4)-ML(2))+
           1     VOLB*CPA*(TATM-AVERAGE(T))/SVA)/(MLCPLAV+MVCPVBA+MACPAV)+T(2)
      C
      C     CALCULATE CORRECTED VALUES
      C
            CALL CORRECT
        120 DELTME=0.0
            MA(4)=MA(2)+(VOLB/SVA)*KOUNT
            PV(4)=CPF(1,T(4))
            PT(4)=PT(2)+MA(4)*RA*(T(4)+273.2)/(VOLT-ML(4)*VL(4))
            ZL(4)=ML(4)*VL(4)/AT
            CALL ZLHCALC
      C
      C     CHECK FOR CONVERGENCE
      C
            IF(ABS ((PT(4)-PT(3))/PT(4)).LE..001)GO TO 1000
            MA(3)=MA(4)
            ZL(3)=ZL(4)
            ZLH(3)=ZLH(4)
            GO TO 105
```

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SUBROUTINE ENERGY2    76/74    OPT=1                    FTN 4.6+433F        80/08/15. 13.45.07        PAGE     2

          C
          C      CONVERGENCE ACHIEVED
          C
           1000 CONTINUE
                RETURN
                END
```

```
      SUBROUTINE FLOW1
C
C     CALLED FUNCTIONS: CPF,CPLHF
      COMMON /GEN/ PT(4),T(4),ZL(4),ZLH(4),MA(4),MV(4),ML(4),PINF,
     1             VW,G,J,CD,AOL,AOG,RG1,RG,TAMB,TIME(4),MOLE,VOLT,
     2             ZW,ZP,DPV,SVD,HTD,CPA,SVL(4),SVV(4),WLO,WVO,WAO,
     3             PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),TC,SVA,
     4             PINFG,ZT,CMI,PA(4)
      COMMON/ING/  DP,TML,TMV,TMA,DML,DMV,DMA,FLOSUB,ENRSUB,AP,INGFLG,
     1             ICT,XLP,DELTME,ZWT(4),VOLB,NTEST,NCHANGE
      REAL MA,MV,ML,MOLE,LAMBDA,J
      AVERAGE(X)=(X(4)+X(2))/2.0
      TSAMB=CPF(6,PINF)
      IF(TSAMB.GT.AVERAGE(T)) GO TO 120
      VLAMB=1./CPF(2,TSAMB)
      VVAMB= CPF(3,TSAMB)*(RG/MOLE)*(TSAMB+273.2)/PINF
      IF(AOL.EQ.0.0) WLO=0.0
      IF(AOL.EQ.0.0) GO TO 121
C  ***LIQUID
      SASL=(CPF(4,T(4))+CPF(4,T(2)))*.5*ALOG((AVERAGE(T)+273.2)/
     1     (TSAMB+273.2))
      VOUTL=VLAMB+SASL*(TSAMB+273.2)*(VVAMB-VLAMB)/CPLHF(TSAMB)*.12
      DUM1=(CPL(2)+CPL(4))*.5*(AVERAGE(T)-TSAMB)-
     1   ((TSAMB+273.2)*SASL)+(AVERAGE(PT)-(CPF(1,T(4))+CPF(1,T(2)))*
     2   .5)/J
     2   *10000.*(1./CPF(2,AVERAGE(T)))+(AVERAGE(ZL)-AVERAGE(ZLH))*G/J
C
      IF(2.*J*DUM1.LT.0.0) INGFLG=2
      IF(INGFLG.EQ.2) RETURN
      WLO=(CD*AOL/VOUTL)*(2.*J*DUM1)**.5
      GO TO 121
  120 DUM1=(10000.*(AVERAGE(PT)-PINF)*(1./CPF(2,AVERAGE(T)))+G*
     1     (AVERAGE(ZL)-AVERAGE(ZLH)))*2.0
      IF(DUM1.LT.0.0) INGFLG=2
      IF(INGFLG.EQ.2) RETURN
      WLO=(CD*AOL*DUM1**.5)/(1./CPF(2,AVERAGE(T)))
  121 IF(AOG.EQ.0.0) WVO=WAO=0.0
      IF(AOG.EQ.0.0) RETURN
C
C  ***VAPOR
C     FIRST CASE
      IF(MA(4).NE.0.0)GO TO 500
      TSAMB=CPF(6,PINFG)
      VLAMB=1./CPF(2,TSAMB)
      VVAMB=CPF(3,TSAMB)*(RG/MOLE)*(TSAMB+273.2)/PINFG
      SVSA= CPF(3,AVERAGE(T))*RG1/MOLE*ALOG(AVERAGE(PT)/PINFG)-
     1   (CPF(5,T(4))+CPF(5,T(2)))*.5*ALOG((AVERAGE(T)+273.2)/
     2   (TSAMB+273.2))
      VOUTV=VVAMB -(SVSA*(TSAMB+273.2))*(VVAMB -VLAMB)/CPLHF(TSAMB)*.12
      DUM2=(((CPF(5,T(4))+CPF(5,T(2)))*.5*(AVERAGE(T)-TSAMB)
     1   +(TSAMB+273.2)*SVSA)*2.0*J
      IF(DUM2.LT.0.0) INGFLG=2
      IF(INGFLG.EQ.2) RETURN
      WVO= (DUM2**.5*CD*AOG)/VOUTV
      WAO=0.0
      RETURN
C
```

```
SUBROUTINE FLOW1       76/74    OPT=1                    FTN 4.6+433F       80/08/15. 13.45.07       PAGE     2

      C     SECOND CASE   MA.NE.0.0
      C
        500 RV=RG/MOLE
            RA=RG/28.96
            RM=( (RV*MV(4) + RA*MA(4))/(MA(4)+ MV(4))+
           1   (  RV*MV(2) + RA*MA(2))/(MA(2)+ MV(2)))/2.0
            DUM3=( MV(4)*CPF(5,T(4)) + MV(2)*CPF(5,T(2)))/2.0 +
           1      ( MA(4)*CPA+MA(2)*CPA)/2.0
            CPM= DUM3 / ((MA(4)+MV(4)+MA(2)+MV(2))/2.0)
      C
            RV1=RG1/MOLF
            RA1=RG1/28.96
            RM1=  ((RV1*MV(4)+RA1*MA(4))/(MA(4)+MV(4)) +
           1        (RV1*MV(2)+RA1*MA(2))/(MA(2)+MV(2)))/2.0
            GAMM= CPM/(CPM-RM1)
            DUM4=(((PINFG/AVERAGE(PT))**(2./GAMM)-(PINFG/AVERAGE(PT))**
           1   ((GAMM+1.)/GAMM))* 2.*GAMM/(GAMM-1.))
            IF(DUM4.LT.0.0) INGFLG=2
            IF(INGFLG.EQ.2) RETURN
            WVO= (100.*AVERAGE(MV)*CD*AOG*AVERAGE(PT)*DUM4**.5)/
           1   ((MV(4)+MA(4)+MV(2)+MA(2))/2. * (RM*(AVERAGE(T)+273.2))**.5)
            WAO= AVERAGE(MA)/AVERAGE(MV)*WVO
            RETURN
            END
```

```
      SUBROUTINE FLOW2
C     CALLED FUNCTIONS: CPF
C
      COMMON /GEN/ PT(4),T(4),ZL(4),ZLH(4),MA(4),MV(4),ML(4),PINF,
     1             VW,G,J,CD,AOL,AOG,RG1,RG,TAMB,TIME(4),MOLE,VOLT,
     2             ZW,ZP,DPV,SVD,HTD,CPA,SVL(4),SVV(4),WLO,WVO,WAO,
     3             PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),TC,SVA,
     4             PINFG,ZT,CMI,PA(4)
      COMMON/ING/  DP,TML,TMV,TMA,DML,DMV,DMA,FLOSUB,ENRSUB,AP,INGFLG,
     1             ICT,XLP,DELTME,ZVT(4),VOLB,NTEST,NCHANGE
C
      REAL MA,MV,ML,MOLE,LAMBDA,J
C     CALCULATE WLO,WVO,WAO
C     LIQUID
      AVERAGE(X)=(X(4)+X(2))/2.0
      NW=12
      A1=(10000.*(AVERAGE(PT)-PINF)*(1./CPF(2,AVERAGE(T)))+G*
     1    (AVERAGE(ZL)-AVERAGE(ZLH)))*2.0
C
      IF(A1.LT.0.0) INGFLG=2
      IF(INGFLG.EQ.2) RETURN
      WLO=(CD*AOL*A1**.5)/(1./CPF(2,AVERAGE(T)))
      IF(AOG.EQ.0.0) WAO=WVO=0.0
      IF(AOG.EQ.0.0) RETURN
C
C     GAS
C
      RV=RG/MOLE
      RA=RG/28.96
      RM= ((RV*MV(4) + RA*MA(4))/(MA(4)+ MV(4))+
     1   (  RV*MV(2) + RA*MA(2))/(MA(2)+ MV(2)))/2.0
      DUM3=( MV(4)*CPF(5,T(4)) + MV(2)*CPF(5,T(2)))/2.0 +
     1     (MA(4)*CPA+MA(2)*CPA)/2.0
      CPM= DUM3 /((MA(4)+MV(4)+MA(2)+MV(2))/2.0)
C
      RV1=RG1/MOLE
      RA1=RG1/28.96
      RM1= ((RV1*MV(4)+RA1*MA(4))/(MA(4)+MV(4)) +
     1      (RV1*MV(2)+RA1*MA(2))/(MA(2)+MV(2)))/2.0
      GAMM=  CPM/(CPM-RM1)
C
      A2=(100.*AVERAGE(MV)*C *AOG*AVERAGE(PT))/((MV(4)+MA(4)+MV(2)+
     1    MA(2))/2.0*(RM*(AVERAGE(T)+273.2))**.5)
      A3=(PINFG/AVERAGE(PT))**(2./GAMM)-(PINFG/AVERAGE(PT))**
     1   ((GAMM+1.)/GAMM)
      IF((2.*GAMM)/(GAMM-1.)*A3.LT.0.0) INGFLG=2
      IF(INGFLG.EQ.2) RETURN
      WVO=A2*     ((2.*GAMM)/(GAMM-1.)*A3) **.5
      WAO=AVERAGE(MA)/AVERAGE(MV)*WVO
      RETURN
      END
```

```
FUNCTION GAMM        76/74    OPT=1                    FTN 4.6+433F        80/08/15. 13.45.07        PAGE     1

              FUNCTION GAMM(RA)
        C     CALLED FUNCTIONS: CPF
              COMMON /GEN/ PT(4),T(4),ZL(4),ZLH(4),MA(4),MV(4),ML(4),PINF,
             1             VW,G,J,CDORF,AOL,AOG,RG1,RG,IATM,TIN(4),MOLE,
             2             VOLT,ZW,ZP,DELPVAL,IVALVE,IHEATER,CPA,VL(4),VV(4),
             3             WLO,WVO,WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),
             4             TC,SVA,PINFG,ZI,CHI
        C     CALCULATE   GAMMA M
              REAL MA,MV,ML,J,MOLE,LAMBDA
              RV1=RG1/MOLE
              RV=RG/MOLE
              RA1=RG1/28.96
              CPVBAR(2)=CPF(5,T(2))
              CPVBAR(4)=CPF(5,T(4))
              RM1=((RV1*MV(2)+RA1*MA(2))/(MA(2)+MV(2))+
             1     (RV1*MV(4)+RA1*MA(4))/(MA(4)+MV(4)))/2.0
              CPM=((MV(2)*CPVBAR(2)+MV(4)*CPVBAR(4))/2.0+
             1       ((MA(2)+MA(4))*CPA/2.0))/
             1     ((MA(2)+MA(4)+MV(2)+MV(4))/2.0)
              GAMM=CPM/(CPM-RM1)
              RETURN
              END
```

```
      SUBROUTINE INGEST
C     CALLED SUBROUTINES: AIRMASS,TERMIN
C     CALLED FUNCTIONS: CPF
      COMMON /GEN/ PT(4),T(4),ZL(4),ZLH(4),MA(4),MV(4),ML(4),PINF,
     1             VW,G,J,CDORF,AOL,AOG,RGI,RG,TINF,TIME(4),CMWT,
     2             VT,ZW,ZP,DPV,SVD,HTD,CPA,SVL(4),SVV(4),WLO,
     3             WVO,WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVDAR(4),
     4             TC,SVA,PINIG,ZT,CMI,PA(4)
      COMMON/ING/  DP,TML,TMV,TMA,DML,DMV,DMA,FLOSUB,ENRSUB,AP,INGFLG,
     1             ICT,XLP,DELTME,ZWT(4),VOLB,NTEST,NCHANGE
      COMMON/WAT/ZLEQI,PTEQI
      INTEGER HTD,SVD,FLOSUB,ENRSUB
      REAL    ML,MV,MA,J,LAMBDA,MLEQI,MAI,MVI
C
      NW=12
      WRITE(12,10)
   10 FORMAT(1H ,14H  .T TO INGEST)
      IF (ZW.GT.(ZP-DP)) GO TO 900
C
C     WATER BELOW PUNCTURE
      IF (ZL(2).GT.ZP) GO TO 150
C
C     INGESTION IMPOSSIBLE
  100 RETURN
C
  150 IF(INGFLG.NE.2.AND.PT(3).GE.PATM) GO TO 100
      IF(INGFLG.EQ.2) GO TO 160
      IF(ZL(3)-ZP+.5*DP+1.0E+4*PT(3)*SVL(3)/G.GT.1.001*
     1     1.0E+4*PATM*SVL(3)/G) GO TO 100
C     SOMETHING HAPPENED...   ONLY PARAMETERS 1 AND 2 ARE VALID.
  160 ICT=ICT-1
      WRITE(12,90) ZL(3),PT(3),SVL(3),PATM
   90 FORMAT(1H ,8H ZL(3)= ,F10.5,8H PT(3)= ,F10.5,/,
     1     9H SVL(3)= ,F10.5,7H PATM= ,F10.5)
      INGFLG=1
      RETURN
C
C
CC
CCC   WATER LEVEL ABOVE PUNCTURE
CC
C
  900 CONTINUE
      IF(ZP.GT.ZW.AND.ZW.GT.ZP-DP) GO TO 2000
C     GO TO 2000 IF WATER INTERSECTS PUNCTURE
      IF(ZL(2).GT.ZP) GO TO 970
C     GO TO 970 IF LIQUID IS ABOVE TOP OF PUNCTURE
      IF(ZP.GE.ZL(2).AND.ZL(2).GT.ZP-DP) GO TO 930
C     GO TO 930 IF LIQUID INTERSECTS PUNCTURE
C     NOW WATER ABOVE TOP AND LIQUID BELOW BOTTOM OF PUNCTURE
      TEST=PATM+1.0E-4*G*(ZW-ZP+0.5*DP)/VW
      IF(INGFLG.EQ.0.AND.PT(3).GE.1.002*TEST) GO TO 100
      IF(INGFLG.NE.0) GO TO 901
      IF(SVL(3).LE.VW) CALL TERMIN(10HINGEST    )
      INGFLG=4
      RETURN
C     IN NOOUT, WATER FLOWS IN AND SINKS  SO EVENTUALLY THE
```

```
C       CARGO LIQUID WHICH FLOATS WILL AGAIN COME OUT.   RETURN MAIN/NOOUT
  901   ICT=ICT-1
        IF(SVL(2).LE.VW) CALL TERMIN(10HINGEST     )
        INGFLG=4
        RETURN
C       WATER IS ABOVE TOP OF PUNCTURE AND LIQUID INTERSECTS PUNCTURE
  930   TEST=PATM+1.0E-4*G*(ZW-0.5*(ZP+ZL(2)-DML*SVL(2)/AT))/VW
        IF(INGFLG.EQ.0.AND.PT(3).GE.TEST) GO TO 100
C       AT THIS POINT THE WATER MAY BE LIGHTER OR HEAVIER THAN THE LIQUID.
C       IF WATER IS LIGHTER, THEN THIS IS LIKE KTYP=4 EXCEPT NO EVAPORATION
C       IS POSSIBLE AND SIMPLE OUTFLOW OCCURS
        ICT=ICT-1
        IF(SVL(2).LT.VW) GO TO 940
        INGFLG=4
        RETURN
  940   MAI=MA(2)
        MVI=MV(2)
        DML=(ZL(2)-ZP+DP)*AT/SVL(2)/10.
        ZLI=ZL(2)   $   PTI=PT(2)
        TTI=T(2)
        RMI=RGI/CMWI
        CPVBAR(2)=CPF(5,TTI)
        CPM=CPVBAR(2)
        GAMMAM=CPM/(CPM-RMI)
        IF(HTD.EQ.-1) GAMMAM=1.0
        TOP=VT-AT*ZLI
        GAMLES=(GAMMAM-1.0)/GAMMAM
  941   ZL(4)=ZL(2)-DML*SVL(2)/AT
        IF(ZL(4).LE.ZP-DP) ZL(4)=ZP-DP
        IF(ZL(4).LE.ZP-DP) DML=(ZL(2)-ZL(4))*AT/SVL(2)
        ML(4)=ML(2)-DML
        MV(4)=MV(2)
        VLAVG=SVL(2)
        ZLAVG=(ZL(2)+ZL(4))*.5
        AOUT=XLP*(ZLAVG-ZP+DP)
        WLO=CDORF*AOUT*(G*(ZLAVG-ZP+DP)*(1.-VLAVG/VW))**.5/VLAVG
        DT=(ZL(2)-ZL(4))/VLAVG/WLO
        TIME(4)=TIME(2)+DT
        IF(SVD.EQ.1) PT(4)=PTI
        IF(SVD.EQ.1) GO TO 945
        PT(3)=PT(2)
  942   BOT=VT-AT*(1.0E+4*VW/G*(PATM-PT(3))+ZW)
        PT(4)=PTI*(TOP/BOT)**GAMMAM
        T(4)=TTI
        IF(HTD.EQ.1)T(4)=(273.2+TTI)*(PT(4)/PTI)**GAMLES-273.2
        IF(ABS((PT(3)-PT(4))/PT(4)).LE..01) GO TO 945
        PT(3)=PT(4)
        GO TO 942
  945   ZLH(4)=(ZL(4)+ZP-DP)*.5
        MA(4)=MAI
        MV(4)=MVI
        PV(4)=PV(2)*PT(4)/PT(2)
        IF(SVD.EQ.1) T(4)=TTI
        ICT=ICT+1
        TML=TML+DML
        SVL(4)=SVL(2)
        SVV(4)=SVV(2)
```

```
C     PARAMETERS SUB 4 MAY BE PRINTED
      IF(ZL(4).LE.ZP-DP) GO TO 946
      GO TO 941
  946 PT(2)=PT(3)=PT(4)
      PV(2)=PV(3)=PV(4)
      T(2)=T(3)=T(4)
      SVL(2)=SVL(3)=SVL(4)
      ML(2)=ML(3)=ML(4)
      MV(2)=MV(3)=MV(4)
      MA(2)=MA(3)=MA(4)
      SVV(2)=SVV(3)=SVV(4)
      TIME(2)=TIME(3)=TIME(4)
      ZL(2)=ZL(3)=ZL(4)
      ZLH(2)=ZLH(3)=ZLH(4)
  960 CALL TERMIN(10HINGEST    )
C
C     WATER AND CARGO ABOVE PUNCTURE
C     AT 970 LIQUID CARGO AND WATER ABOVE TOP OF PUNCTURE
  970 TEST=SVL(4)*(ZW-ZLH(2))/VW+1.OE+4*SVL(4)*(PATM-PT(4))/G
      IF(INGFLG.EQ.O.AND.ZL(4)-ZLH(2).GT.TEST) GO TO 100
      IF(IML.GT.0) GO TO 980
      IF(NTEST.EQ.1) GO TO 980
      ICT=ICT-1
      INGFLG=4
      RETURN
  980 ICT=ICT-1
C     PARAMETERS SUB 1 AND 2 ARE OK. EQUILIB VALUES ARE DETERMINED BY
C     INTERPOLATION
      X2=ML(1)-ML(2)
      Y1=ZL(1)-ZLH(1)-SVL(1)*(ZW-ZLH(1))/VW-1.E+4*SVL(1)*(PATM-PT(1))/G
      Y2=ZL(2)-ZLH(2)-SVL(2)*(ZW-ZLH(2))/VW-1.E+4*SVL(2)*(PATM-PT(2))/G
      DMLEQ=X2*Y1/(Y1-Y2)-X2
C     EVAPORATION IS NOT CONSIDERED
      WLOEQ=(ML(1)-ML(2))/(TIME(2)-TIME(1))
      IF(INGFLG.EQ.0) WLOEQ=WLO
      DTEQ=DMLEQ/WLOEQ
      TIMEEQ=TIME(2)+DTEQ
      DMVEQ=WVO*DTEQ
      DMAEQ=WAO*DTEQ
      ZLEQI=ZL(2)-DMLEQ*SVL(2)/AT
      PTEQI=1.E-4*G*((ZLH(2)-ZLEQI)/SVL(2)+(ZW-ZLH(2))/VW)+PATM
      IF(SVD.EQ.1.AND.PTEQI.LT.PATM-DPV) PTEQI=PATM-DPV
      TEQI-T(2)
      MLEQI=ML(2)-DMLEQ
      ZLHEQI=ZLH(2)
      INGFLG=3
      RETURN
C
C     CALCULATE LIQUID LEVEL SATISFYING EQUILIBRIUM CONDITION
C
C
 2000 CONTINUE
C     WATER INTERSECTS THE PUNCTURE
      IF(ZL(2).LE.ZP-DP) GO TO 2300
      IF(ZL(2).LE.ZW) GO TO 2200
      IF(ZL(2).GT.ZW.AND.ZL(2).LE.ZP) GO TO 2100
C     NOW ENTER THE FOLLOWING WITH ZL(2).GT.ZP
```

```
      IF(INGFLG.NE.2.AND.ZL(4).LE.ZP) GO TO 2100
      IF(INGFLG.NE.2.AND.PT(4).GE.PATM) GO TO 100
      GO TO 150
 2100 IF(INGFLG.NE.2.AND.ZL(4).LT.ZW) GO TO 2200
C     LIQUID AND WATER INTERSECT PUNCTURE WITH LIQUID ABOVE WATER
      IF(SVL(2).GT.VW) GO TO 2150
      IF(INGFLG.NE.2.AND.PT(4).GT.PATM) GO TO 100
C     ADMIT AIR UNTIL PT(2)=PATM. REINITIATE 3 AND 4 VALUES AND GO TO 300 TVENT
      ICT=ICT-1
      INGFLG=5
      PT(4)=PATM
      PV(4)=PV(2)
      ML(4)=ML(2)
      T(4)=T(2)
      CALL AIRMASS
      PT(2)=PATM
      MA(2)=MA(4)
      PT(1)=PATM
      PINF=PATM
      RETURN
 2150 TEST=(SVL(4)/VW-1.)*.5*(ZW-ZP+DP)+SVL(4)*1.E+4*(PATM-PT(4))/G
      IF(INGFLG.NE.2.AND.ZL(4)-ZW.GT.TEST) GO TO 100
      DO 21501 I=3,4
      ML(I)=ML(I-1)
      MV(I)=MV(I-1)
      MA(I)=MA(I-1)
      T(I)=T(I-1)
      ZL(I)=ZL(I-1)
      ZLH(I)=ZLH(I-1)
      SVL(I)=SVL(I-1)
21501 SVV(I)=SVV(I-1)
      PT(5)=PT(4)
      ZL1=ZL(2)
      ZWT(2)=ZWT(4)=0.
      DT=TIME(4)-TIME(2)
      IF( TIME(4).NE.TIME(2)) GO TO 2152
      IF(WLO.GT.0.) GO TO 2151
      IF(WVO.EQ.C.)DT=1.0
      IF(WVO.EQ.0.) GO TO 2152
      DT=DMV/WVO
      GO TO 2152
 2151 DT=DML/WLO
 2152 CONTINUE
      IF(INGFLG.NE.2.AND.PT(4).GT.PATM) GO TO 2153
      IF(INGFLG.NE.2.AND.PT(4).LE.PATM) PT(2)=PT(4)=PATM
      IF(PT(2).LE.PATM) PT(2)=PT(4)=PATM
 2153 IF(PT(2).LE.PATM) GO TO 2158
C     ASSUME CARGO NOT VOLATILE AND VENT VAPOR ONLY THRU (ZP-ZL1)*XLP
C     OR (ZP-ZL(2))*XLP, WHICH EVER IS LARGER. VENT VAPOR OVER TIME STEPS
C     DT UNTIL PT(4).LE.PATM.
C     FOLLOWING IS VAPOR VENT IF IT OCCURS
      RV1=RG1/CMW1
      RV=RG/CMWT
      RM1=(RV1*MV(2)+RA1*MA(2))/(MV(2)+MA(2))
      RM=(RV*MV(2)+RA*MA(2))/(MV(2)+MA(2))
      CPM=(MV(2)*CPF(5,T(2))+MA(2)*CPA)/(MV(2)+MA(2))
      GAMM=CPM/(CPM-RM1)
```

```
      AOG=(ZP-ZLI)*XLP
      DUM=(ZP-ZL(2))*XLP
      IF(DUM.GT.AOG) AOG=DUM
 2154 AVGMV=(MV(2)+MV(4))*.5
      AVGPT=(PT(2)+PT(4))*.5
      AVGT=(T(2)+T(4))*.5+273.2
      AVGMA=(MA(2)+MA(4))*.5
      A2=(100.*AVGMV* CDORF*AOG*AVGPT)/((AVGMA+AVGMV)*(RM*AVGT )**.5)
      A3=(PATM/AVGPT)**(2./GAMM)-(PATM/AVGPT)**((GAMM+1.)/GAMM)
      A3=AMAX1(0.0,A3)
      WVO=A2*SQRT(2.*GAMM*A3/(GAMM-1.))
      WAO=WVO*AVGPA/AVGMV
      MA(4)=MA(2)-WAO*DT
      MV(4)=MV(2)-WVO*DT
      VM1=(VT  -ZLI*AT)/(MV(2)+MA(2))
      VM2=(VT  -ZLI*AT)/(MV(4)+MA(4))
      PT(4)=PT(2)*(VM1/VM2)**GAMM
      T(4)=T(2)
      TT2=T(2)+273.2
      IF(HTD    .EQ.1)T(4)=TT2*(PT(4)/PT(2))**((GAMM-1.)/GAMM)-273.2
      IF(ABS(MV(2)+MV(4)-AVGMV*2.)/AVGMV/2..GE..01)GO TO 2154
 2158 IF(ZWT(2).GE.ZW)ZLI=(ZL(1)+ZL(2))*.5
      AOUT=(ZLI-ZW)*XLP
      WLO=AOUT*CDORF*(G*(ZLI-ZW))**.5/SVL(2)
      WW=SVL(2)*WLO/VW
      ZWT(4)=ZWT(2)+VW*WW*DT/AT
      ZL(4)=ZL(2)-WLO*DT*SVL(2)/AT
      IF(ZWT(4).LT.ZW) ZL(4)=ZL(2)
      ML(4)=ML(2)-WLO*DT
      ML(3)=ML(4)   $  MV(3)=MV(4)   $  MA(3)=MA(4)   $  PT(3)=PT(4)
      T(3)=T(4)   $  ZL(3)=ZL(4)   $  ZLH(3)=ZLH(4)
      TIME(3)=TIME(4)=TIME(2)+DT   $  ICT=ICT+1
      PV(3)=PV(4)=CPF(1,T(4))
      SVL(3)=SVL(4)=SVL(2)   $   SVV(3)=SVV(4)=(VT   -ZLI*AT)/MV(4)
      TML=TML+WLO*DT
      TMV=TMV+WVO*DT
      TMA=TMA+WAO*DT
C     PRINTOUT OF PARAMETERS SUB 4 AND TML,TMV,TMA MAY BE DONE HERE
      IF(ZWT(4).GE.ZW.AND.ZL(4).LE.ZW) GO TO 2161
C     SCROLL AND CONTINUE
      DO 2160 I=1,3
      ML(I)=ML(I+1) $ MV(I)=MV(I+1) $ MA(I)=MA(I+1)
      PT(I)=PT(I+1) $ T(I)=T(I+1) $ ZL(I)=ZL(I+1) $ ZLH(I)=ZLH(I+1)
      TIME(I)=TIME(I+1) $ PV(I)=PV(I+1)
 2160 SVV(I)=SVV(I+1)
      GO TO 2153
 2161 CALL TERMIN(10HINGEST    )
 2200 IF(INGFLG.NE.2.AND.ZL(4).LT.ZP-DP) GO TO 2300
C     WATER AND LIQUID INTERSECT PUNCTURE WITH WATER ABOVE LIQUID CARGO
      IF(SVL(2).LE.VW) GO TO 2210
      GO TO 2260
 2210 TEST=PATM+1.0E-4*G*(ZW-ZL(4))/VW*.5
      IF(INGFLG.NE.2.AND.PT(4).GT.TEST) GO TO 100
      ICT=ICT-1
      PT(2)=PATM
      ZWT(2)=ZW
      DT=TIME(4)-TIME(2)
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      IF( TIME(4).GE.TIME(2))GO TO 2212
      IF(WLO.GT.0.) GO TO 2211
      IF(WVO.EQ.0.) DT=1.0
      IF(WVO.EQ.0.) GO TO 2212
      DT=DMV/WVO
      GO TO 2212
 2211 DT=DML/WLO
 2212 CONTINUE
      WAO=WVO=0.0
      ZL(4)=ZL(2)
 2213 ZLAVGO=(ZL(4)+ZL(2))*.5
      AOUT=XLP*(ZLAVGO-ZP+DP)
      WLO=AOUT*CDORF*(G*(ZLAVGO-ZP+DP)*(1.-SVL(2)/VW))**0.5/SVL(2)
      ZL(4)=ZL(2)-WLO*DT*SVL(2)/AT
      IF(ZL(4).LE.ZP-DP) CALL TERMIN(10HINGEST     )
      IF(ABS(ZL(4)-2.*ZLAVGO-ZL(2)).GE.0.01*ZL(4))GO TO 2213
 2214 ML(4)=ML(2)-WLO*DT  $  ML(1)=ML(2)  $  ML(2)=ML(4)
      ML(3)=ML(4)
      MV(3)=MV(4)=MV(2)
      MV(1)=MV(2)
      MA(3)=MA(4)=MA(2)   $   MA(1)=MA(2)
      PT(3)=PT(4)=PT(2)   $   PT(1)=PT(2)
      ZL(3)=ZL(4)   $   ZL(1)=ZL(2)   $   ZL(2)=ZL(4)
      T(3)=T(4)=T(2)   $   T(1)=T(2)
      ZLH(3)=ZLH(4)=(ZL(4)+ZP-DP)*0.5   $ ZLH(1)=ZLH(2) $ZLH(2)=ZLH(4)
      TIME(3)=TIME(4)=TIME(2)+DT $ TIME(1)=TIME(2) $ TIME(2)=TIME(4)
      PV(3)=PV(4)=PV(2)  $  PV(1)=PV(2)
      SVL(3)=SVL(4)=SVL(2)  $  SVL(1)=SVL(2)
      SVV(3)=SVV(4)=SVV(2)   $  SVV(1)=SVV(2)
      TML=TML+WLO*DT
C     PRINT PARAMETERS 2 HERE
      GO TO 2213
 2260 TEST=PATM+1.0E-4*G*(ZW-ZL(4))/VW*0.5
      IF(INGFLG.NE.2.AND.PT(4).GT.TEST) GO TO 100
      ICT=ICT-1
      PT(2)=PATM
      ZWT(2)=AMAX1(0.0,ZW-ZL(2))
      AOUT=0.5*(ZW-ZP+DP)*XLP  $  ZL(2)=ZW
      DO 22601 I=3,4
      ML(I)=ML(I-1)  $  MV(I)=MV(I-1)  $  MA(I)=MA(I-1)
      T(I)=T(I-1)  $  ZL(I)=ZL(I-1)  $  ZLH(I)=ZLH(I-1)
      SVL(I)=SVL(I-1)  $  SVV(I)=SVV(I-1)  $  ZWT(I)=ZWT(I-1)
22601 PT(I)=PT(I-1)
      DT=TIME(4)-TIME(2)
      IF(TIME(.).NE.TIME(2)) GO TO 2262
      IF(WLO.GT.0.) GO TO 2261
      IF(WVO.EQ.0.) DT=1.0
      IF(WVO.EQ.0.) GO TO 2262
      DT=DMV/WVO
      GO TO 2262
 2261 DT=DML/WLO
 2262 AC=AOUT*CDORF/VW*SQRT(2.*G*(1.-VW/SVL(2)))
      AB=AC*SQRT(0.5*(ZW-ZP+DP))
 2263 WW=AB $  ZWTAVG=(ZWT(2)+ZWT(4))*0.5
      IF(ZWTAVG.GT.ZP-DP) WW=AC*SQRT((ZW-ZWTAVG)*(0.5*(ZW-ZWTAVG)
     1  -(ZP-DP))/(ZW-ZP+DP))
      ZWT(4)=VW*WW*DT/AT + ZWT(2)
```

AD-A095 413 SOUTHWEST RESEARCH INST SAN ANTONIO TEX F/G 13/10
EXPERIMENTAL VERIFICATION AND REVISION OF THE VENTING RATE MODE--ETC(U)
NOV 80 F T DODGE, E B BOWLES, J E MANN DOT-CG-73623-A
UNCLASSIFIED SWRI-02-5295 USCG-D-63-80 NL

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      IF(ABS(ZWT(4)-2.*ZWTAVG-ZWT(2)).GE.0.01*ZWT(4)) GO TO 2263
      WLO=WW*SVL(2)/VW
      ZL(4)=ZL(2)   $   ZL(3)=ZL(2)
      ML(4)=ML(2)-WLO*DT   $  ML(3)=ML(4)
      ICT=ICT+1
      TIME(3)=TIME(4)=TIME(2)+DT   $  ZWT(3)=ZWT(4)
      TML=TML+WLO*DT
C     PRINTOUT OF PARAMETERS SUB 4 AND TML,TMV,TMA MAY BE DONE
      IF(ZWT(4).GE.ZW) GO TO 2264
C     SCROLL
      DO 2264 I=1,3
      ML(I)=ML(I+1) $ MV(I)=MV(I+1) $  MA(I)=MA(I+1)   $  PT(I)=PT(I+1)
      ZWT(I)=ZWT(I+1)
      T(I)=T(I+1) $ ZL(I)=ZL(I+1) $ ZLH(I)=ZLH(I+1)
      TIME(I)=TIME(I+1)
      PV(I)=PV(I+1)  $  SVL(I)=SVL(I+1) $ SVV(I)=SVV(I+1)
      GO TO 2263
 2264 CALL TERMIN(10HINGEST    )
 2300 CONTINUE
C     WATER INTERSECTS PUNCTURE AND LIQUID CARGO IS BELOW THE BOTTOM
C     OF THE PUNCTURE
      TEST=PATM+1.0E-4*G*0.5*(ZW-ZP+DP)/VW
      IF(INGFLG.NE.2.AND.PT(4).GT.1.002*TEST) GO TO 100
      IF(ZL(2).EQ.0.0) GO TO 2264
      IF(SVL(2).GT.VW) GO TO 2360
C     WATER LIGHTER- ONLY GAS MAY FLOW OUT
      AOUT=XLP*(ZP-ZW)    $    ICT=ICT-1   $  AOG=AOUT
      RV1=RG1/CMWT $ RV=RG/CMWT $ RA1=RG1/28.96   $   RA=RG/28.96
      RM1=(RV1*MV(2)+RA1*MA(2))/(MV(2)+MA(2))
      RM=(RV*MV(2)+RA*MA(2))/ (MV(2)+MA(2))
      CPM=(MV(2)*CPF(5,T(2))+MA(2)*CPA)/(MA(2)+MV(2))
      GAMM=CPM/(CPM-RM1)
      PT(2)=PT(2)*((ZT-ZL(2))/(ZT-ZW))**GAMM
C     GAMM TRANSFERRED FROM
      ML(3)=ML(4)=ML(2)   $  WLO=0.0
      ZL(3)=ZL(4)=ZL(2)     $     SVV(3)=SVV(4)=SVV(2)
      ZLH(3)=ZLH(4)=ZLH(2)   $   MV(3)=MV(4)=MV(2)
      SVL(3)=SVL(2)=SVL(4)     $     MA(3)=MA(4)=MA(2)
      PT(3)=PT(4)=PT(2)     $     T(3)=T(4)=T(2)
      IF(WVO.EQ.0.) DT=1.0  $  ZWT(3)=ZWT(4)=ZWT(2)= ZW
      IF(WVO.EQ.0.) GO TO 2310
      DT=DMV/WVO
 2310 CONTINUE
 2311 RM1=(RV1*MV(2)+RA1*MA(2))/(MV(2)+MA(2))
      RM=(RV*MV(2)+RA*MA(2))/ (MV(2)+MA(2))
      CPM=(MV(2)*CPF(5,T(2))+MA(2)*CPA)/(MA(2)+MV(2))
      GAMM=CPM/(CPM-RM1)
      AVGMV=(MV(2)+MV(4))*0.5  $   AVGPT=(PT(2)+PT(4))*0.5
      AVGT=(T(2)+T(4))*0.5+273.2   $   AVGMA=(MA(2)+MA(4))*0.5
      A2=(100.*AVGMV*CDORF*AOG*AVGPT)/((AVGMA+AVGMV)*(RM*AVGT)**0.5)
      A3=(PATM/AVGPT)**(2./GAMM)-(PATM/AVGPT)**((GAMM+1.)/GAMM)
 2312 A3=AMAX1(0.0,A3)
      WVO=A2*SQRT(2.*GAMM*A3/(GAMM-1.))
      WAO=WVO*AVGMA/AVGMV
      MA(4)=MA(2)-WAO*DT
      MV(4)=MV(2)-WVO*DT
      VM1=(VT  -ZL(2)*AT)/(MV(2)+MA(2))
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      VM2=(VT  -ZL(4)*AT)/(MV(4)+MA(4))
      PT(4)=PT(2)*(VM1/VM2)**GAMM
      T(4)=T(2)  $  TT2=T(2)+273.2
      IF(MTD    .EQ.1) T(4)=TT2*(PT(4)/PT(2))**((GAMM-1.0)/GAMM)-273.2
      IF(ABS(MV(2)+MV(4)-AVGMV*2.)/AVGMV/2.0.GE.0.01) GO TO 2311
      ICT=ICT+1
      TMV=TMV+MVO*DT
      TMA=TMA+MAO*DT
C     SCROLL , PRINT , CHECK, THEN ALLOW FOR 2311
 2360 ZL(4)=ZP-DP
      GO TO 2260
      END
```

```
      SUBROUTINE HONENER(ITIME)
C
C     DETERMINES PRESSURE AND TEMPERATURE OF THE TANK CARGO
C     AS LIQUID OR VAPOR IS VENTED.
C
C     CALLED SUBROUTINES: FLOW2,TERMIN,ZLNCALC
C     CALLED FUNCTIONS: CPF,GAMM
      REAL LAMBDA,J,MOLE,MA,ML,MV
      COMMON /GEN/ PT(4),T(4),ZL(4),ZLN(4),MA(4),MV(4),ML(4),PINF,
     1             VW,G,J,CDORF,AOL,AOG,RG1,RG,TATM,TIN(4),MOLE,
     2             VOLT,ZW,ZP,DELPVAL,IVALVE,IHEATTR,CPA,VL(4),VV(4),
     3             WLO,WVO,WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),
     4             TC,SVA,PINFG,ZT,CHI,PA(4)
      COMMON/ING/  DP,TML,TMV,TMA,DML,DMV,DMA,FLOSUB,ENRSUB,AP,INGFLG,
     1             ICT,XLP,DELTME,ZNT(4),VOLD,NTEST,NCHANGE
      AVERAGE(X)=(X(2)+X(4))/2.0
      RA=RG/28.96
      RV=RG/MOLE
C
C     IS VALVE UNSTUCK?
C
      IF (IVALVE.EQ.1)GO TO 310
C
C     RELIEF VALVE STUCK
C     IS TANK LIQUID LEVEL PARTIALLY BELOW PUNCTURE
C
      IF((ZL(4)-ZP+DP).LE.0.0.AND.WVO.LE.0.0) CALL TERMIN(10H MAIN      )
      IF(ZL(4).LE.ZP)GO TO 200
C
C     ADIABATIC PROCESS
C     SECTION 1.1 TANK LIQUID LEVEL IS ABOVE PUNCTURE
C     COMPUTE GAMM FOR INITIAL ITERATION
  104 WA=WAO=WVO=0.0
      MA(4)=MA(3)=MA(2)=MA(1)
      MV(4)=MV(3)=MV(2)=MV(1)
  105 GAMMAN=GAMM(RA)
C
      IF(IHEATTR.EQ.-1) GAMMAN=1.0
      OLDWLO=WLO
      VL(2)=1./CPF(2,TC)
      VL(4)=1./CPF(2,TC)
      CALL FLOW2
      IF(INGFLG.EQ.2) RETURN
      IF(WLO.GT.0.0) GO TO 125
      DT=DMV/WVO
      DML=WLO*DT
      DMA=WAO*DT
      GO TO 130
  125 DT=DML/WLO
      DMV=WVO*DT
      DMA=WAO*DT
  130 CONTINUE
      ML(4)=ML(2)-WLO*DT
      PT(4)=PT(2)*((VOLT-ML(2)*VL(2))/(VOLT-ML(4)*VL(4)))**GAMMAN
      T(4)=(T(2)+273.2)/(PT(2)/PT(4))**((GAMMAN-1.)/GAMMAN)-273.2
      ZL(4)=ML(4)*VL(4)/AT
      CALL ZLNCALC
```

```
      WA=WAO=WVO=0.0
C
C     CHECK FOR CONVERGENCE
C
      IF(ABS(WLO-OLDWLO).LE.(.001*OLDWLO)) GO TO 1000
      PT(3)=PT(4)
      ML(3)=ML(4)
      T(3)=T(4)
      VL(3)=VL(4)
      ZL(3)=ZL(4)
      ZLN(3)=ZLN(4)
      GO TO 105
  200 CONTINUE
C
C     SECTION 1.2 TANK LIQUID LEVEL IS AT LEAST PARTIALLY BELOW PUNCTURE
C                     AND PT.GT.PATM
      IF(PT(4).LE.PATM) GO TO 300
  205 OLDWLO=WLO
      CALL FLOW2
      IF(INGFLG.EQ.2) RETURN
      IF(WLO.GT.0.0) GO TO 225
      DT=DMV/WVO
      DML=WLO*DT
      DMA=WAO*DT
      GO TO 230
  225 DT=DML/WLO
      DMV=WLO*DT
      DMA=WAO*DT
  230 CONTINUE
      MA(4)=MA(2)-WAO*DT
      MV(4)=MV(2)-WVO*DT
      GAMMAM=GAMM(RA)
C     CHECK FOR ISOTHERMAL OPTION
      IF(IHEATTR.EQ.-1) GAMMAM=1.0
      VL(2)=1./CPF(2,T(2))
      VL(4)=1./CPF(2,T(4))
      ML(4)=ML(2)-WLO*DT
      VM1=(VOLT-ML(2)*VL(2))/(MV(2)+MA(2))
      VM2=(VOLT-ML(4)*VL(4))/(MV(4)+MA(4))
      PT(4)=PT(2)*(VM1/VM2)** GAMMAM
      ZL(4)=ML(4)*VL(4)/AT
      CALL ZLNCALC
C
C     CHECK FOR CONVERGENCE
C
      IF(ABS(WLO-OLDWLO).LE.(.001*OLDWLO)) GO TO 1000
      MA(3)=MA(4)
      MV(3)=MV(4)
      ML(3)=ML(4)
      PT(3)=PT(4)
      T(3)=T(4)
      VL(3)=VL(4)
      ZL(3)=ZL(4)
      ZLN(3)=ZLN(4)
      GO TO 205
  300 CONTINUE
C
```

```
      C     SECTION I.3 TANK LIQUID LEVEL IS AT LEAST PARTIALLY BELOW PUNCTURE
      C                 AND  PT = PATM
      C     CHECK FOR ISOTHERMAL OPTION
            IF(PT(4).LT.PATM) PT(4)=PATM
            IF(INEATTR.EQ.-1)GAMMAM=1.0
        305 OLDWLO=WLO
            CALL FLOW2
            IF(INGFLG.EQ.2) RETURN
            IF(WLO.GT.0.0) GO TO 307
            DT=DMV/WVO
            DML=WLO*DT
            DMA=WAO*DT
            GO TO 308
        307 DT=DML/WLO
            DMV=WVO*DT
            DMA=WAO*DT
        308 CONTINUE
            ML(4)=ML(2)-WLO*DT
            PT(4)=PATM
            ZL(4)=ML(4)* VL(4)/AT
            CALL ZLNCALC
            WA=WAO=WVO=0.0
      C
      C     CHECK FOR CONVERGENCE
      C
            IF(ABS(WLO-OLDWLO).LE.(.001*OLDWLO)) GO TO 1000
            MA(3)=MA(4)=MA(2)
            MV(3)=MV(4)=MV(2)
            PT(3)=PT(4)
            ML(3)=ML(4)
            T(3)=T(4)
            ZL(3)=ZL(4)
            ZLN(3)=ZLN(4)
            GO TO 305
        310 CONTINUE
      C
      C*****RELIEF VALVE UNSTUCK*****
      C
      C     SECTION II.1 PUNCTURE BELOW TANK LIQUID LEVEL AND
      C                  PT.GT. PATM-DELPVAL
      C
            IF(ZL(4).GT.ZP.AND.PT(4).GT.(PATM-DELPVAL)) GO TO 104
        350 CONTINUE
      C
      C     SECTION II.2 PUNCTURE BELOW TANK LIQUID LEVEL OR
      C                  PT = PATM-DELPVAL
            OLDWLO=WLO
            GAMMAM=GAMM(MA)
            IF((ZL(4)-ZP+DP).LE.0.0.AND.WVO.LE.0.0) CALL TERMIN(10H MAIN      )
            IF(ZL(4).LT.ZP) GO TO 400
            IF(PT(4).LT.(PATM-DELPVAL)) PT(4)=PATM-DELPVAL
            WAO=WVO=0.0
            CALL FLOW2
            IF(INGFLG.EQ.2) RETURN
            IF(WLO.GT.0.0) GO TO 362
            DT=DMV/WVO
            DML=WLO*DT
```

```
      DMA=WAO*DT
      GO TO 363
  362 DT=DML/WLO
      DMV=WVO*DT
      DMA=WAO*DT
  363 CONTINUE
      PT(4)=PT(3)=PATM-DELPVAL
      T(4)=(T(2)+273.2)/(PT(2)/PT(4))**((GAMMAM-1.)/GAMMAM)-273.2
      MA(4)=(PT(4)-PV(4))*(VOLT-ML(4)*VL(4))/(RA*(T(4)+273.2))
      ML(4)=ML(2)-WLO*DT
      ZL(4)=ML(4)*VL(4)/AT
      CALL ZLNCALC
C
C     CHECK FOR CONVERGENCE
C
      IF(ABS(WLO-OLDWLO).LE.(.001*OLDWLO)) GO TO 1000
      PT(3)=PT(4)
      ML(3)=ML(4)
      T(3)=T(4)
      ZL(3)=ZL(4)
      ZLN(3)=ZLN(4)
      GO TO 350
  400 CONTINUE
C
C     SECTION II.3 TANK LIQUID LEVEL IS AT LEAST PARTIALLY BELOW PUNCTURE
C                  AND PT.GT.PATM
C
      IF(PT(4).GT.PATM) GO TO 200
C
C     SECTION II.4 PUNCTURE BECOMES PARTIALLY BELOW LIQUID LEVEL AND
C                  PT = PATM-DELPVAL
C
      PT(4)=PATM
      PT(2)=PATM-DELPVAL
      IF(ITIME.NE.1) PT(4)=PT(2)=PATM
      T(4)=(T(2)+273.2)/(PT(2)/PT(4))**((GAMMAM-1.)/GAMMAM)-273.2
      MA(4)=(PT(4)-PV(4))*(VOLT-ML(4)*VL(4))/(RA*(T(4)+273.2))
      CALL FLOW2
      IF(INGFLG.EQ.2) RETURN
      IF(WLO.GT.0.0) GO TO 515
      DT=DMV/WVO
      DML=WLO*DT
      DMA=WAO*DT
      GO TO 520
  515 DT=DML/WLO
      DMV=WVO*DT
      DMA=WAO*DT
  520 CONTINUE
      ML(4)=ML(2)-WLO*DT
      ZL(4)=ML(4)*VL(4)/AT
      CALL ZLNCALC
C
C     CONVERGENCE ACHIEVED
C
 1000 CONTINUE
      RETURN
  700 WRITE(12,710) PT(3),PT(4),PATM,ZL(3),ZL(4),ZP
```

```
      710 FORMAT(1H ,26H ERROR IN CHECK STATEMENTS,/,
         1       8H PT(3)= ,F15.5,8H PT(4)= ,F15.5,7H PATH= ,F15.5,/,
         2       8H ZL(3)= ,F15.5,8H ZL(4)= ,F15.5,5H ZP= ,F15.5)
          RETURN
          END
```

```
      SUBROUTINE NONENG2(KOUNT)
C     CALLED SUBROUTINES: ZLHCALC
C     CALLED FUNCTIONS: CPF,GAMM
      REAL LAMBDA,MA,ML,MV,J,MOLE
      COMMON /GEN/ PT(4),T(4),ZL(4),ZLH(4),MA(4),MV(4),ML(4),PINF,
     1             VW,G,J,CDORF,AOL,AOG,RG1,RG,TATM,TIN(4),MOLE,
     2             VOLT,ZW,ZP,DELPVAL,IVALVE,IHEATTR,CPA,VL(4),VV(4),
     3             WLO,WVO,WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),
     4             TC,SVA,PINFG,ZT,CMI,PA(4)
      COMMON/ING/  DP,IML,IMV,IMA,DML,DMV,DMA,FLOSUB,ENRSUM,AP,INGFLG,
     1            ICT,XLP,DELTME,ZUT(4),VOLB,NTEST,NCHANGE
      AVERAGE(X)=(X(2)+X(4))/2.0
      NW=12
      RA=RG/28.96
      RV=RG/MOLE
      PT(3)=PT(4)
 104  VLI=1.0/CPF(2,TC)
      WA=WAO=WVO=WLO=0.0
C
C     PUNCTURE BELOW TANK LIQUID LEVEL
C
 105  GAMMAN=GAMM(RA)
      IF(IHEATTR.EQ.-1) GAMMAN=1.0
      ML(4)=ML(2)
      MV(4)=MV(2)
      MA(4)=MA(2)+(VOLB/SVA)*KOUNT
      PV(4)=CPF(1,T(4))
      VM1=(VOLT-ML(2)*VLI)/(MA(2)+MV(2))
      VM2=(VOLT-ML(2)*VLI)/(MA(2)+MV(2)+VOLB/SVA)
      PT(4)=PT(2)*(VM1/VM2)**GAMMAN
      T(4)=(T(2)+273.2)/(PT(2)/PT(4))**((GAMMAN-1.)/GAMMAN)-273.2
      ZL(4)=ML(4)*VLI/AT
      CALL ZLHCALC
C
C     CHECK FOR CONVERGENCE
C
      IF(ABS((PT(4)-PT(3))/PT(4)).LE..001) GO TO 1000
      PT(3)=PT(4)
      MA(3)=MA(4)
      MV(3)=MV(4)
      ML(3)=PL(4)
      T(3)=T(4)
      VL(3)=VL(4)
      ZL(3)=ZL(4)
      ZLH(3)=ZLH(4)
      GO TO 105
C
C     CONVERGENCE ACHIEVED
C
 1000 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE NOOUT
C     CALLED SUBROUTINES: TERMIN
C     CALLED FUNCTIONS: GAMM
      COMMON /GEN/ PT(4),T(4),ZL(4),ZLH(4),MA(4),MV(4),ML(4),PINF,
     1             VW,G,J,CDORF,AOL,AOG,RG1,RG,TINF,TIM(4),CHWT,
     2             VT,ZW,ZP,DPV,SVD,NTD,CPA,SVL(4),SVV(4),WLO,
     3             WVD,WAO,PATM,AT,PV(4),LAMDA(4),CPL(4),CPVBAR(4),
     4             TC,SVA,PINFG,ZT,CHI,PA(4)
      COMMON/ING/  DP,TML,TMV,TMA,DML,DMV,DMA,FLOSUB,ENRSUB,AP,INGFLG,
     1             ICT,XLP,DELTME,ZWT(4),VOLB,NTEST,NCHANGE
      COMMON/WAT/  ZLEQI,PTEQI
      INTEGER NTD,SVD,FLOSUB,ENRSUB
      REAL    ML,MV,MA,J,LAMDA
      AVERAGE(X)=(X(2)+X(4))/2.0
      WRITE(12,15)
   15 FORMAT(13H GOT TO NOOUT)
      RA=RG/28.96
      PI=ACOS(-1.0)
      WW=0.0
      ATOT=AP
      PTINT=PT(2)
      ZLINT=ZL(2)
      IF(SVL(4).GT.VW) GO TO 500
C     CASE I. WATER LIGHTER THAN CARGO
C     CHECK IF RELIEF VALVE IS STUCK
      ZWT(1)=ZWT(2)=ZWT(3)=ZWT(4)=ZL(4)
      IF(SVD.EQ.-1)GO TO 200
      ZWTEQ=ZW-(VW/SVL(4)-1.)*(ZLINT-ZLH(4))+10000.*(PINF-PTINT)*VW/G
   25 IF(ZWTEQ.GT.ZT)GO TO 100
      ZWTI=1.1*(ZWTEQ-ZLH(4))+ZLH(4)
   50 SQ2=(.2*G*(ZWTEQ-ZLH(4)))**.5
      SQ1=(2.*G*(VW/SVL(4)-1.)*(AVERAGE(ZL)-AVERAGE(ZLH)))**.5
      AIN=ATOT*VW*SQ2/(SQ1*SVL(4)+SQ2*VW)
      AOUT=ATOT-AIN
      WLO=CDORF*AOUT*SQ2/SVL(4)
      OLDWW=WW
      WW=WLO
      IF(TIM(4).NE.0.0) GO TO 52
      DT=DML/WLO
      TIM(4)=TIM(2)+DT
   52 ML(4)=ML(2)-WLO*DT
      ZL(4)=ZLINT-WLO*SVL(4)*DT/AT
      ZLH(4)=ZP-DP*.5
      IF(ZL(4).LT.ZP) ZLH(4)=.5*(ZL(4)+ZP-DP)
      IF(ZL(4).LT.ZP) ATOT=(ZL(4)-ZP+DP)*XLP
      IF(ABS(WW-OLDWW).GT.(.001*OLDWW))GO TO 50
C     SCROLL PARAMETERS
      ZL(1)=ZL(2)
      ML(1)=ML(2)
      ZLH(1)=ZLH(2)
      TIM(1)=TIM(2)
      ZL(2)=ZL(3)=ZL(4)
      ML(2)=ML(3)=ML(4)
      ZLH(2)=ZLH(3)=ZLH(4)
      TIM(2)=TIM(3)=TIM(4)
      TML=TML+DML
      TIM(4)=TIM(2)+DT
```

```
      WRITE(12,7200) TIM(2),ML(2),MV(2),MA(2),TML,TMV,TMA,T(2),PT(2),
     1       ZL(2)
      IF(ZL(4).GT.(ZP-DP))GO TO 50
      CALL TERMIN(10H NOOUT    )
      GO TO 2500
  100 CONTINUE
C     ZWTEQ.GT.ZT
      ZLN(4)=ZP-DP*.5
      AIN=AP*.5
      IF(DP.EQ.0..AND.ZL(4).LT.ZP) GO TO 108
      IF(ZL(4).LT.ZP)ZLN(4)=.5*(ZL(4)+ZP-DP*.5)
      IF(ZL(4).LT.ZP) AIN=((ZP-ZL(4))+.5*(ZL(4)-ZP+DP))*XLP
      SQ1=(2.*((PINF-PTINT)*VW*10000.+G*(ZW-ZT)-G*(1./SVL(4)-
     1    1./VW)*(AVERAGE(ZL)-ZLN(4))))**.5
      OLDWW=WW
      WW=CDORF*AIN*SQ1/VW
      WLO=VW*WW/SVL(4)
      IF(TIM(4).NE.0.0) GO TO 104
      DT=DML/WLO
      TIM(4)=TIM(2)+DT
  104 ML(4)=ML(2)-WLO*DT
      ZL(4)=ZL(2)-VW*WW*DT/AT
      IF(ABS(WW-OLDWW).GT.(.001*OLDWW)) GO TO 100
      TIM(1)=TIM(2)
      ZL(1)=ZL(2)
      ML(1)=ML(2)
      ZLN(1)=ZLN(2)
      TIM(2)=TIM(3)=TIM(4)
      ZL(2)=ZL(3)=ZL(4)
      ML(2)=ML(3)=ML(4)
      ZLN(2)=ZLN(3)=ZLN(4)
      TIM(4)=TIM(2)+DT
      TML=TML+DML
      WRITE(12,7200) TIM(2),ML(2),MV(2),MA(2),TML,TMV,TMA,T(2),PT(2),
     1       ZL(2)
      IF(ZL(4).GT.ZP-DP) GO TO 100
  108 CALL TERMIN(10H NOOUT    )
      GO TO 2500
C     SECTION 1.0
C     RELIEF VALVE IS STUCK
C     CALCULATE PT BY ITERATION ROUTINE
  200 GAMMAN=GAMM(KA)
      ZWTEQ2=(ZLINT+ZT)*.5
  202 ZWTEQ1=ZWTEQ2
      PT(4)=PTINT*((VT-AT*ZLINT)/(VT-AT*ZWTEQ1))**GAMMAN
      ZWTEQ2=ZW-(VW/SVL(4)-1.)*(ZLINT-ZLN(4))+10000.*VW*(PINF-PT(4))/G
      IF(ABS(ZWTEQ2-ZWTEQ1).GT.(.001*ZWTEQ1)) GO TO 202
      ZWTEQ=ZWTEQ2
      GO TO 25
C
  500 CONTINUE
C     CARGO LIGHTER THAN WATER  VL.GT.VW
C     CHECK IF RELIEF VALVE IS STUCK
C
      ZWT(1)=ZWT(2)=ZWT(3) ZWT(4)=0.0
      IF(SVD.EQ.-1) GO TO 700
      DELZLT=SVL(4)/VW*(ZW-ZP)-10000.*SVL(4)/G*(PTINT-PINF)
```

```
 501  DEL1=ZLINT-DELZLT
      DEL2=ZLINT-(ZT-ZP)
      DEL3=DELZLT-(ZT-ZP)
      IF(DEL1.LE.0.0.AND.DEL2.LE.0.0)GO TO 520
      IF(DEL1.GE.0.0.AND.DEL3.LE.0.0)GO TO 530
      IF(DEL1.LE.0.0.AND.DEL2.GT.0.0)GO TO 540
      IF(DEL1.GE.0.0.AND.DEL3.GE.0.0)GO TO 540
C
C     ERROR IN CHECK STATEMENTS
      WRITE(12,503)DEL1,DEL2,DEL3
 503  FORMAT(1H ,7HDEL1 = ,F12.5,8H DEL2 = ,F12.5,8H DEL3 = ,F12.5)
      GO TO 2500
C     SECTION II.A I
 520  CONTINUE
C     CARGO LIFTED ENTIRELY ABOVE PUNCTURE, NO CARGO ESCAPES
      WRITE(12,521)
 521  FORMAT(1H ,50H WATER ENTERS TANK AND LIFTS CARGO ABOVE PUNCTURE.,
     1 /,21H CARGO DOES NOT VENT.)
      CALL TERMIN(10H NOOUT    )
      GO TO 2500
C
C     SECTION II.A  II
 530  CONTINUE
C     WEIGHT OF CARGO IS SUFFICIENT TO BALANCE WATER PRESSURE
      ZWTINT=ZP-DEL1
      ZWT(2)=ZWT(3)=ZWT(4)=ZWTINT
      ZL(4)=ZLINT+ZWTINT
      ZLN(4)=ZP-DP*.5
 532  IF(ZWT(4).GT.(ZP-DP))GO TO 535
C
C     HEIGHT OF WATER IN TANK IS LESS THAN BOTTOM OF PUNCTURE
C
      OLDWW=WW
      WW=CDORF*AP/(2.*VW)*(G*(1.-VW/SVL(4))*(ZP-DP/2.-ZWT(4)))**.5
      WLO=VW*WW/SVL(4)
      IF(TIM(4).NE.0.0) GO TO 533
      DT=DML/WLO
      TIM(4)=TIM(2)+DT
 533  ML(4)=ML(2)-WLO*DT
      ZWT(4)=ZWT(2)+WW*DT*VW/AT
      WRITE(12,51) T(2),T(4),DELTME,ML(2),ML(4),MV(2),MV(4),PT(2),
     1              PT(4),PV(2),PV(4),ZL(2),ZL(4),ZLN(2),ZLN(4),
     2              ZWT(2),ZWT(4),WLO,WW
      IF(ABS(WW-OLDWW).GT.(.001*OLDWW))GO TO 532
C     SCROLL PARAMETERS
      ZWT(1)=ZWT(2)
      ML(1)=ML(2)
      TIM(1)=TIM(2)
      ZWT(2)=ZWT(3)=ZWT(4)
      ML(2)=ML(3)=ML(4)
      TIM(2)=TIM(3)=TIM(4)
      TML=TML+DML
      TIM(4)=TIM(2)+DT
      WRITE(12,7200) TIM(2),ML(2),MV(2),MA(2),TML,TMV,TMA,T(2),PT(2),
     1     ZL(2)
      IF(ZWT(4).LT.ZP)GO TO 532
      CALL TERMIN(10H NOOUT    )
```

```
      GO TO 2500
  535 CONTINUE
      OLDWW=WW
      WW=CDORF*AP/(2.*VW)* (2.*G*(1.-VW/SVL(4))*(ZP-AVERAGE(ZWT)))**.5
      WLO=VW*WW/SVL(4)
      IF(TIM(4).NE.0.0) GO TO 536
      DT=DML/WLO
      TIM(4)=TIM(2)+DT
  536 ML(4)=ML(2)-WLO*DT
      ZWT(4)=ZWT(2)+WW*AT*VW/DT
      WRITE(12,51) T(2),T(4),DELTME,ML(2),ML(4),MV(2),MV(4),PT(2),
     1              PT(4),PV(2),PV(4),ZL(2),ZL(4),ZLH(2),ZLH(4),
     2              ZWT(2),ZWT(4),WLO,WW
   51 FORMAT(1H ,8H T(2)=  ,E12.5,8H T(4)=  ,E12.5,9H DELTME= ,E12.5,/,
     1            8H ML(2)= ,E12.5,8H ML(4)= ,E12.5,/,
     2            8H MV(2)= ,E12.5,8H MV(4)= ,E12.5,/,
     3            8H PT(2)= ,E12.5,8H PT(4)= ,E12.5,/,
     4            8H PV(2)= ,E12.5,8H PV(4)= ,E12.5,/,
     5            8H ZL(2)= ,E12.5,8H ZL(4)= ,E12.5,/,
     6            9H ZLH(2)= ,E12.5,9H ZLH(4)= ,E12.5,/,
     7            9H ZWT(2)= ,E12.5,9H ZWT(4)= ,E12.5,6H WLO= ,E12.5,
     8            6H WW=  ,E12.5)
      IF(ABS(WW-OLDWW).GT.(.001*OLDWW)) GO TO 535
      ZWT(1)=ZWT(2)
      ML(1)=ML(2)
      TIM(1)=TIM(2)
      ZWT(2)=ZWT(3)=ZWT(4)
      ML(2)=ML(3)=ML(4)
      TIM(2)=TIM(3)=TIM(4)
      TIM(4)=TIM(2)+DT
      TML=TML+DML
      WRITE(12,7200) TIM(2),ML(2),MV(2),MA(2),TML,TMV,TMA,T(2),PT(2),
     1    ZL(2)
 7200 FORMAT(1H ,10E12.5)
      IF(ZWT(4).LT.ZP) GO TO 535
      CALL TERMIN(10H NOOUT    )
      GO TO 2500
C
C     SECTION II.A III
  540 CONTINUE
      ZWTINT=ZT-ZLINT
  542 IF(ZWT(4).GT.ZP-DP) GO TO 545
C
C     HEIGHT OF WATER IN TANK IS LESS THAN BOTTOM OF PUNCTURE
C
      OLDWW=WW
      AT=((10000.*(PINF-PTINT)*VW+G*(ZW-ZP+DP/2.)-G*(VW/SVL(4)*
     1   (ZT-ZP+DP/2.)))*2.)**.5
      WW=CDORF*AP*AT/(2.*VW)
      WLO=VW*WW/SVL(4)
      IF(TIM(4).NE.0.0) GO TO 545
      DT=DML/WLO
      TIM(4)=TIM(2)+DT
  545 ML(4)=ML(2)-WLO*DT
      ZWT(4)=ZWT(2)+VW*WW*DT/AT
      IF(ABS(WW-OLDWW).GT.(.001*OLDWW))GO TO 542
      ZWT(1)=ZWT(2)
```

```
      ML(1)=ML(2)
      TIM(1)=TIM(2)
      ZWT(2)=ZWT(3)=ZWT(4)
      ML(2)=ML(3)=ML(4)
      TIM(2)=TIM(3)=TIM(4)
      TIM(4)=TIM(2)+DT
      TML=TML+DML
      WRITE(12,7200) TIM(2),ML(2),MV(2),MA(2),TML,TMV,TMA,T(2),PT(2),
     1   ZL(2)
      IF(ZWT(4).LT.ZP)GO TO 542
  545 CONTINUE
      OLDWW=WW
      A2=(2.*(10000.*(PINF-PTINT)+VW*G*(ZW-ZT+VW/SVL(4))-
     1    G*(1.-VW/SVL(4))*((ZP-AVERAGE(ZWT))**2/(2.*DP)-
     2    AVERAGE(ZWT))))**.5
      WW=CDORF*AP*A2/(2.*VW)
      WLO=VW*WW/SVL(4)
      IF(TIM(4).NE.0.0) GO TO 575
      DT=DML/WLO
      TIM(4)=TIM(2)+DT
  575 ML(4)=ML(2)-WLO*DT
      ZWT(4)=ZWT(2)+VW*WW*DT/AT
      IF(ABS(WW-OLDWW).GT.(.001*OLDWW))GO TO 545
      ZWT(1)=ZWT(2)
      ML(1)=ML(2)
      TIM(1)=TIM(2)
      ZWT(2)=ZWT(3)=ZWT(4)
      ML(2)=ML(3)=ML(4)
      TIM(2)=TIM(3)=TIM(4)
      TIM(4)=TIM(2)+DT
      TML=TML+DML
      WRITE(12,7200) TIM(2),ML(2),MV(2),MA(2),TML,TMV,TMA,T(2),PT(2),
     1   ZL(2)
      IF(ZWT(4).LT.ZP)GO TO 545
      CALL TERMIN(10N NOOUT    )
      GO TO 2500
C
  700 CONTINUE
C
C     SECTION II.B
C     CARGO LIGHTER THAN WATER  VL.GT.VW
C     RELIEF VALVE IS STUCK
C     CALCULATE PT BY ITERATION ROUTINE
      IF(ZL(2).LE.ZP-DP)GO TO 800
      GAMMAM=GAMM(RA)
      DELZLT2=SVL(4)/VW*(ZW-ZP)-10000.*SVL(4)*(PTINT-PATM)/G
  701 DELZLT1=DELZLT2
      PT(4)=PTINT*((VT-AT*ZLINT)/(VT-AT*(DELZLT1+ZP)))**GAMMAM
      DELZLT2=SVL(4)/VW*(ZW-ZP)-10000.*SVL(4)*(PT(4)-PATM)/G
      IF(ABS(DELZLT2-DELZLT1).GT. (.001*DELZLT1))GO TO 701
      DELZLT=DELZLT2
      GO TO 501
  800 PT(4)=PTINT
      ZWTINT=ZP-ZLINT
      DT=AT*ZWTINT/WVO
      MV(4)=WVO*DT
      DMV=DT*WVO
```

```
              B1=10000.*SVL(2)*(PTINT-PATM)
              B2=DP*.5-SVL(2)*(ZW-ZP+DP*.5)/VW
              WLO=AP/SVL(2)*(B1+B2)**.5
              DT=(ZP-ZWTINT)*AT/WLO
              ML(4)=WLO*DT
              DML=DT*WLO
              WRITE(12,900) ZWTINT,PTINT,WLO,ZLINT,ML(4),MV(4)
          900 FORMAT(1H ,6E12.4)
              RETURN
         2500 END
```

```
      SUBROUTINE SCROLL
C
C     SCROLLS PARAMETERS TO RESTART PROGRAM IN A
C     DIFFERENT KTYP
C
      COMMON /GEN/ PT(4),T(4),ZL(4),ZLH(4),MA(4),MV(4),ML(4),PINF,
     1             VW,G,J,CDORF,AOL,AOG,RG1,RG,TINF,TIME(4),CMUT,
     2             VT,ZW,ZP,DPV,SVD,NTD,CPA,SVL(4),SVV(4),WLO,WVO,
     3             WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),TC,SVA,
     4             PINFG,ZT,CRI,PA(4)
      COMMON /ING/ DP,TML,TMV,TMA,DML,DMV,DMA,FLOSUB,ENRSUB,AP,INGFLG,
     1             ICT,XLP,DELTME,ZUT(4),VOLU,NIEST,NCHANGE
      INTEGER NTD,PDTSC,PE,SVD,FLOSUB,ENRSUB
      REAL ML,MV,MA,J,LAMBDA
      WRITE(12,20)
   20 FORMAT(1H ,13HGOT TO SCROLL)
      DO 100 I=2,4
      ML(I-1)=ML(I)
      MV(I-1)=MV(I)
      MA(I-1)=MA(I)
      PT(I-1)=PT(I)
      T(I-1)=T(I)
      ZL(I-1)=ZL(I)
      ZLH(I-1)=ZLH(I)
      PA(I-1)=PA(I)
      TIME(I-1)=TIME(I)
      PV(I-1)=PV(I)
      SVL(I-1)=SVL(I)
      SVV(I-1)=SVV(I)
      CPL(I-1)=CPL(I)
      CPVBAR(I-1)=CPVBAR(I)
  100 CONTINUE
      ML(2)=ML(3)=ML(4)
      MV(2)=MV(3)=MV(4)
      MA(2)=MA(3)=MA(4)
      PT(2)=PT(3)=PT(4)
      T(2)=T(3)=T(4)
      ZL(2)=ZL(3)=ZL(4)
      ZLH(2)=ZLH(3)=ZLH(4)
      PA(2)=PA(3)=PA(4)
      TIME(2)=TIME(3)=TIME(4)
      PV(2)=PV(3)=PV(4)
      SVL(2)=SVL(3)=SVL(4)
      SVV(2)=SVV(3)=SVV(4)
      CPL(2)=CPL(3)=CPL(4)
      CPVBAR(2)=CPVBAR(3)=CPVBAR(4)
      TML=TML+DML
      TMV=TMV+DMV
      TMA=TMA+DMA
  200 FORMAT(4E15.5)
      WRITE(12,200)ML(1),ML(2),ML(3),ML(4)
      WRITE(12,200)MV(1),MV(2),MV(3),MV(4)
      WRITE(12,200)MA(1),MA(2),MA(3),MA(4)
      WRITE(12,200) PT(1),PT(2),PT(3),PT(4)
      WRITE(12,200)T(1),T(2),T(3),T(4)
      WRITE(12,200)ZL(1),ZL(2),ZL(3),ZL(4)
      WRITE(12,200)ZLH(1),ZLH(2),ZLH(3),ZLH(4)
```

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SUBROUTINE SCROLL     76/74   OPT=1                    FTN 4.6+433F      80/08/15. 13.45.07      PAGE     2

                  WRITE(12,200)PA(1),PA(2),PA(3),PA(4)
                  WRITE(12,200)TIME(1),TIME(2),TIME(3),TIME(4)
                  WRITE(12,200)PV(1),PV(2),PV(3),PV(4)
                  WRITE(12,200)SVL(1),SVL(2),SVL(3),SVL(4)
                  WRITE(12,200)SVV(1),SVV(2),SVV(3),SVV(4)
                  WRITE(12,200)CPL(1),CPL(2),CPL(3),CPL(4)
                  WRITE(12,200)CPVBAR(1),CPVBAR(2),CPVBAR(3),CPVBAR(4)
                  WRITE(12,200)TML,TMV,TMA
                  END
```

SUBROUTINE TERMIN 76/74 OPT=1 FTN 4.6+433F 80/08/15. 13.45.07 PAGE 1

```
      SUBROUTINE TERMIN(ENDCODE)
      COMMON /GEN/ PT(4),T(4),ZL(4),ZLN(4),MA(4),MV(4),ML(4),PINF,
     1             VN,G,J,CDORF,ADL,ADG,RG1,RG,TINF,TIME(4),CHNT,
     2             VT,ZU,ZP,DPV,SVD,NTD,CPA,SVL(4),SVV(4),WLO,WVO,
     3             WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),TC,SVA,
     4             PINFG,ZT,CHI
      COMMON/ING/  DP,TML,TMV,TMA,DML,DMV,DMA,FLOSUB,ENRSUB,AP,INGFLG,
     1             ICT,XLP,DELTME,INT(4),VOLO,NTEST,NCHANGE
      INTEGER  NTD,SVD,FLOSUB,ENRSUB
      REAL ML,MV,MA,J,LAMBDA
      NW=12
      WRITE(NW,5000)ENDCODE
      WRITE(NW,5100) (TIME(I),I=1,4)
      WRITE(NW,5110) (ML(I),I=1,4)
      WRITE(NW,5120) (MV(I),I=1,4)
      WRITE(NW,5130) (MA(I),I=1,4)
      WRITE(NW,5140)(PT(I),I=1,4)
      WRITE(NW,5150)(PV(I),I=1,4)
      WRITE(NW,5160)(ZL(I),I=1,4)
      WRITE(NW,5170)(T(I),I=1,4)
C
      WRITE(NW,5200)TIME(2),TML,TMV,TMA
C
 5000 FORMAT(1H1,44X,22HTVENT TERMINATED FROM  ,A20,//,46X,
     1             34HVALUES OF PARAMETERS AT RUN COMPLETION // )
 5100 FORMAT( 6HDTIME ,4E15.5)
 5110 FORMAT(23HDLIQUID MASS REMAINING ,4E15.5)
 5120 FORMAT(22HDVAPOR MASS REMAINING ,4E15.5)
 5130 FORMAT(17HDAIR MASS IN TANK ,4E15.5)
 5140 FORMAT(15HDTANK PRESSURE ,4E15.5)
 5150 FORMAT(16HDVAPOR PRESSURE ,4E15.5)
 5160 FORMAT(16HDLIQUID LEVEL  ,4E15.5)
 5170 FORMAT(20HDCARGO TEMPERATURE  ,4E15.5)
 5200 FORMAT(19HDTOTAL VENT TIME = ,E15.5,/23H TOTAL MASS LOST(L,V,A),
     1       3E15.5)
C
      STOP
      END
```

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```
      SUBROUTINE WATIN
C     CALLED SUBROUTINES: TERMIN,ZLNCALC
C     CALLED FUNCTIONS: CPF,GAMM
      COMMON /GEN/ PT(4),T(4),ZL(4),ZLN(4),MA(4),MV(4),ML(4),PINF,
     1             VW,G,J,CDORF,AOL,AOG,RG1,RG,TINF,TIM(4),CMUI,
     2             VT,IW,IP,DPV,SVD,NID,CPA,SVL(4),SVV(4),WLO,
     3             VWO,WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),
     4             TC,SVA,PINFG,ZI,CHI,PA(4)
      COMMON/ING/  DP,TML,TMV,TMA,DML,DMV,DMA,FLOSUM,ENRSUM,AP,INGFLG,
     1             ICT,NLP,DELTME,ZWT(4),VULN,NTEST,NCHANGE
      COMMON/WAT/  ZLEQI,PTEQI
      INTEGER NID,SVD,FLOSUM,ENRSUM
      REAL    ML,MV,MA,J,LAMBDA,KT
      AVERAGE(X)=(X(2)+X(4))/2.0
      WRITE(12,10)
   10 FORMAT(1H ,13H GOT TO WATIN)
      KT=85.
      RA=RG/28.96
C     CHECK IF WATER IS HEAVIER THAN CARGO
C
      IF(SVL(4).GT.VW) GO TO 500
C
C     CASE I. WATER LIGHTER THAN CARGO
C     CHECK IF RELIEF VALVE IS STUCK
      IF(SVD.EQ.-1)GO TO 300
C
C     RELIEF VALVE UNSTUCK
C
      VW=0.0
      PTINT=PTEQI+(PT(2)-PTEQI)/KT
      ZLINT=ZLEQI+(ZL(2)-ZLEQI)/KT
      PT(4)=PT(3)=PT(2)+PTINT
      T(4)=T(3)=T(2)
      ZWT(1)=ZWT(2)=ZWT(3)=ZWT(4)=ZL(2)
      ZL(4)=ZL(2)
      ATOT=AP
   25 SQ1=(2.*G*(VW/SVL(4)-1.)*(AVERAGE(ZL)-AVERAGE(ZLN)))**.5
      SQ2=(2.*(10000.*SVL(4)*(PTINT-PTEQI)+G*(ZLINT-ZLEQI)))**.5
      OLDVW=VW
      AIN=ATOT*VW*SQ2/(SVL(4)*SQ1+VW*SQ2)
      AOUT=ATOT-AIN
      WLO=CDORF*AOUT*SQ2/SVL(4)
      VW=WLO
      DT=TIM(4)-TIM(2)
      DML=WLO*DT
      ML(4)=ML(2)-WLO*DT
      ZL(4)=ZL(2)-WLO*DT*SVL(4)/AT
      CALL ZLNCALC
      ZWT(4)=ZWT(2)+VW*DT*VW/AT +ZL(4)-ZL(2)
      IF(ABS(VW-OLDVW).GT.(.001*OLDVW)) GO TO 25
      DO 210 I=2,4
      ML(I-1)=ML(I)
      ZL(I-1)=ZL(I)
      ZLN(I-1)=ZLN(I)
      TIM(I-1)=TIM(I)
      ZWT(I-1)=ZWT(I)
  210 CONTINUE
```

```
      ML(2)=ML(3)=ML(4)
      ZL(2)=ZL(3)=ZL(4)
      ZLN(2)=ZLN(3)=ZLN(4)
      TIM(2)=TIM(3)=TIM(4)
      ZWT(2)=ZWT(3)=ZWT(4)
      TML=TML+DML
      WRITE(12,7200) TIM(2),ML(2),MV(2),MA(2),TML,TMV,TMA,T(2),PT(2),
     1     ZL(2)
      IF(ZL(4).GT.ZP-DP) GO TO 25
      CALL TERMIN(10H WATIN     )
      RETURN
C
  300 CONTINUE
C     WATER LIGHTER THAN CARGO
C     RELIEF VALVE STUCK
C
      PTINT=PTEQI+(PT(2)-PTEQI)/KT
      ZLINT=ZLEQI+(ZL(2)-ZLEQI)/KT
      GAMMAN=1.0
      IF(NID.EQ.1) GAMMAN=GAMM(RA)
      PT(4)=PT(3)=PT(2)
      ZWT(1)=ZWT(2)=ZWT(3)=ZWT(4)=ZL(2)
      ZL(4)=ZL(2)
      ATOT=AP
  350 PT(3)=PT(4)
      SVL(4)=1./CPF(2,T(4))
      SQ1=(2.*G*(VW/SVL(4)-1.)*(AVERAGE(ZL)-AVERAGE(ZLN)))**.5
      SQ2=((10000.*SVL(4)*(PTINT-PTEQI)+G*(ZLINT-ZLEQI))*2.)**.5
      GW=G*(VT-AT*AVERAGE(ZWT))/AT +10000.*GAMMAN*SVL(4)*AVERAGE(PT)
      GL=G*(VT-AT*AVERAGE(ZWT))/AT +10000.*GAMMAN*VW*AVERAGE(PT)
      AIN=(ATOT*SQ2*GW*VW)/(SVL(4)*GL*SQ1+VW*SQ2*GW)
      AOUT=ATOT-AIN
      WLO=CDORF*AOUT*SQ2/SVL(4)
      WW=CDORF*AIN*SQ1/VW
      DT=TIM(4)-TIM(2)
      DML=WLO*DT
      ML(4)=ML(2)-WLO*DT
      ZL(4)=ZL(2)-WLO*(TIM(4)-TIM(2))*SVL(4)/AT
      CALL ZLNCALC
      ZWT(4)=ZWT(2)+WW*(TIM(4)-TIM(2))*VW/AT+ZL(4)-ZL(2)
      GAMMAN=1.0
      IF(NID.EQ.1)GAMMAN=GAMM(RA)
      PT(4)=PTINT*((VT-AT*ZLINT)/(VT-AT*ZWT(4)))**GAMMAN
      T(4)=(T(2)+273.2)/(PT(2)/PT(4))**((GAMMAN-1.)/GAMMAN)-273.2
      IF(ABS((PT(4)-PT(3))/PT(4)).GT..002) GO TO 350
      DO 710 I=2,4
      ML(I-1)=ML(I)
      MV(I-1)=MV(I)
      MA(I-1)=MA(I)
      PT(I-1)=PT(I)
      T(I-1)=T(I)
      ZL(I-1)=ZL(I)
      ZLN(I-1)=ZLN(I)
      PA(I-1)=PA(I)
      TIM(I-1)=TIM(I)
      PV(I-1)=PV(I)
      SVL(I-1)=SVL(I)
```

```
      SVV(I-1)=SVV(I)
      CPL(I-1)=CPL(I)
      CPVBAR(I-1)=CPVBAR(I)
      ZWI(I-1)=ZWI(I)
  710 CONTINUE
      PT(2)=PT(3)=PT(4)
      T(2)=T(3)=T(4)
      ML(2)=ML(3)=ML(4)
      MA(2)=MA(3)=MA(4)
      MV(2)=MV(3)=MV(4)
      PV(2)=PV(3)=PV(4)
      TIM(2)=TIM(3)=TIM(4)
      ZL(2)=ZL(3)=ZL(4)
      ZLN(2)=ZLN(3)=ZLN(4)
      PA(2)=PA(3)=PA(4)
      SVL(2)=SVL(3)=SVL(4)
      SVV(2)=SVV(3)=SVV(4)
      CPL(2)=CPL(3)=CPL(4)
      CPVBAR(2)=CPVBAR(3)=CPVBAR(4)
      ZWI(2)=ZWI(3)=ZWI(4)
      TML=TML+DML
      WRITE(12,7200) TIM(2),ML(2),MV(2),MA(2),TML,TMV,TMA,T(2),PT(2),
     1               ZL(2)
      TIM(4)=TIM(2)+DT
      IF(ZL(4).GT.ZP-DP) GO TO 350
      CALL TERMIN(CION WATIN    )
      RETURN
  500 CONTINUE
C
C     WATER HEAVIER THAN CARGO
C     SAME SOLUTION FOR RELIEF VALVE STUCK OR UNSTUCK
C
      WW=0.0
      ATOT=AP
      PTINT=PTEQI+(PT(2)-PTEQI)/KT
      ZLINT=ZLEQI+(ZL(2)-ZLEQI)/KT
      ZWI(4)=ZWI(3)=ZWI(2)=ZWI(1)=0.0
  510 SQ2=(2.*(10000.*SVL(4)*(PTINT-PTEQI)+G*(ZLINT-ZLEQI)))**.5
      IF(AVERAGE(ZLN).LE.AVERAGE(ZWI))GO TO 820
      SQ3=(2.*G*(1.-WW/SVL(4))*(AVERAGE(ZLN)-AVERAGE(ZWI)))**.5
      OLDWW=WW
      AIN=ATOT*SQ2/(SQ3+SQ2)
      AOUT=ATOT-AIN
      WLG=CDORF*ACUT*SQ2/SVL(4)
      WW=CDORF*AIN*SQ3/VW
      DT=TIM(4)-TIM(2)
      DML=WLG*GT
      ML(4)=ML(2)-WLG*DT
      ZWI(4)=VW*WW*DT/AT + ZWI(2)
      IF(ABS(WW-OLDWW).GT.(.001*OLDWW)) GO TO 510
      DO 810 I=2,4
      ML(I-1)=ML(I)
      TIM(I-1)=TIM(I)
      ZWI(I-1)=ZWI(I)
  810 CONTINUE
      TML=TML+DML
      ML(2)=ML(3)=ML(4)
```

```
      TIM(2)=TIM(3)=TIM(4)
      ZWT(2)=ZWT(3)=ZWT(4)
 7200 FORMAT(1H ,10E12.5)
      TIM(4)=TIM(2)+DT
      WRITE(12,7200) TIM(2),ML(2),MV(2),MA(2),TML,TMV,TMA,T(2),PT(2),
     1     ZL(2)
      IF(ZWT(4).LT.ZP) GO TO 510
  820 CALL TERMIN(10H WATIN    )
      RETURN
      END
```

```
      SUBROUTINE ZLNCALC
      COMMON /GEN/ PT(4),T(4),ZL(4),ZLN(4),MA(4),MV(4),ML(4),PINF,
     1             VW,G,J,COOBF,AOL,AOG,RGI,RG,TATM,TIN(4),MOLE,
     2             VOLT,ZW,ZP,DELPVAL,IVALVE,IHEATTR,CPA,VL(4),VV(4),
     3             WLO,WVO,WAO,PATM,AT,PV(4),LAMBDA(4),CPL(4),CPVBAR(4),
     4             TC,SVA,PINFG,ZT,CHI,PA(4)
      COMMON/ING/  DP,IML,IMV,IMA,DML,DMV,DMA,FLOSUB,ENRSUB,AP,INGFLG,
     1             ICT,XLP,DELINE,ZWT(4),VOLB,NTEST,NCHANGE
      REAL J,LAMBDA,MA,ML,MOLE,MV
C     PUNCTURE NOT SUBMERGED BY WATER
      IF (ZW.GT.ZP-DP) GO TO 330
C     CARGO BELOW PUNCTURE
      IF (ZL(4).GT.ZP-DP) GO TO 310
      KTYP=8
      GO TO 400
C     CARGO ABOVE PUNCTURE
  310 CONTINUE
      IF (ZL(4).LT.ZP) GO TO 320
      ZLN(4)=ZP-0.5*DP
      KTYP=1
      GO TO 400
C     CARGO INTERSECTS PUNCTURE
  320 CONTINUE
      ZLN(4)=0.5*(ZL(4)+ZP-DP)
      KTYP=4
      GO TO 400
C
C   ***
C     PUNCTURE SUBMERGED BY WATER
  330 CONTINUE
      IF (ZW.LT.ZP)  GO TO 360
C     CARGO BELOW PUNCTURE
      IF (ZL(4).GT. ZP-DP) GO TO 340
      KTYP=9
      GO TO 400
C     CARGO ABOVE PUNCTURE
  340 CONTINUE
      IF (ZL(4).LT.ZP) GO TO 350
      ZLN(4)=ZP-DP*0.5
      KTYP=2
      GO TO 400
C     CARGO INTERSECTS PUNCTURE
  350 ZLN(4)=(ZL(4)+ZP-DP)*0.5
      KTYP=5
      GO TO 400
C   ***
C     PUNCTURE INTERSECTS WATER LEVEL
C     CARGO BELOW PUNCTURE
  360 CONTINUE
      IF (ZL(4).GT. ZP-DP) GO TO 370
      KTYP=10
      GO TO 400
C     CARGO ABOVE PUNCTURE
  370 CONTINUE
      IF(ZL(4).LT.ZP) GO TO 380
      ZLN(4)=ZP-.5*DP
      KTYP=3
```

```
SUBROUTINE ZLNCALC     76/74    OPT=1                         FTN 4.6+433F       80/08/15. 13.45.07       PAGE     2

                  GO TO 400
            C     CARGO INTERSECTS PUNCTURE,BUT IS ABOVE WATER
              380 CONTINUE
                  IF (ZL(4).LT.ZW) GO TO 390
                  ZLN(4)=0.5*(ZL(4)+ZP-DP)
                  KTYP=6
                  GO TO 400
            C     CARGO INTERSECTS PUNCTURE,BUT IS BELOW WATER
              390 ZLN(4)=(ZL(4)+ZP-DP)*.5
                  KTYP=7
            C   ***
              400 CONTINUE
                  RETURN
                  END
```

APPENDIX D. SENSITIVITY ANALYSIS OF MODEL

The sensitivity of the model predictions to slight changes in the initial conditions was determined by the method described in [2]. That is, one of the inputs supplied by the user, say, the cargo temperature, was changed by some percentage and the change in the output, say total mass released or total discharge time, was computed. A sensitivity coefficient was then defined as

$$S = (\Delta\phi/\phi_n)/(\Delta x/x_n) \quad . \tag{D.1}$$

where ϕ is the output and x is the input. The subscript n refers to the nominal value of x or ϕ. A value of S = 1 means that the output changes by the same percentage as the input, S = 2 means that the output percentage change is twice the input change, and so on. Strictly speaking, equation (D.1) defines the "first order sensitivity coefficients" because changes in the output as a result of the interaction of changes in two or more inputs are not considered.

In this analysis, only the sensitivity coefficients for the input selected by the user will be determined. The sensitivity to the various internal parameters of the model, say, the Chemical Properties File correlations, will not be determined since these are presumed to be "accurate." Changes in the numerical scheme will not be investigated either because a predictor-corrector type of integration is employed in which the discharge mass increment is changed automatically within the program to ensure that the changes in tank pressure and liquid level during each time step remain relatively constant; this kind of numerical integration avoids the sensitivity problems of numerical integration that are discussed in [2]. The sensitivity of the results to changes in the various empirical constants of the model was discussed in the main text; since

the "best" values have already been incorporated in the model, the sensitivity of the output to these parameters is not relevant.

The sensitivity coefficients were computed for a tank containing LNG, which is a volatile cargo displaying most of the thermodynamic interactions of interest; adiabatic conditions were assumed. The nominal input conditions were:

V_T, Tank volume = 2×10^8 cm^3

Z_T, Tank height = 700 cm

A_p, Circular puncture area = 2688 cm^3

Z_p, Puncture centerline elevation = 175 cm

C_D, Discharge coefficient = 0.68

Relief valve = stuck

M_i, Initial cargo mass = 8×10^7 grams

T_i, Initial temperature = -159.2°C = 114°K

P_{atm}, Atmospheric pressure = 101.3565 KPa

T_{atm}, Air temperature = 21°C = 294.2°K

All the input parameters were varied by ±5% except for the temperature, which was varied by ±1% of its absolute value; the large change of LNG vapor pressure with temperature at pressures near atmospheric required a smaller percentage change for T_i than for the other inputs. The relief valve was always kept "stuck" to emphasize two-phase flow effects; it ought to be realized, however, that when the relief valve is functioning it controls the vapor space pressure, and the sensitivity of the output to the initial temperature (i.e., the saturation pressure) is much diminished. For all the calculations, the puncture was open to the atmosphere (nonsubmerged puncture). Note that the nominal value of temperature was taken as 114°K, rather than as -159.2°C, so that the sensitivity coefficients will be

positive if the output increases when the temperature increases, and vice versa.

Only the sensitivity coefficients for the liquid outflow duration of the discharge are presented here. After the tank liquid level falls below the puncture, LNG vapor is slowly discharged until all the remaining liquid is boiled away. The sensitivity coefficients for the entire discharge are, consequently, not very revealing. Sensitivity coefficients for the total mass discharged are all zero (e.g., all the initial mass is discharged, regardless of the initial conditions), except for the two coefficients related to the changes in the initial mass, which are both one. All the sensitivity coefficients for the total discharge time are nearly zero (because the boil-off time of the liquid dominates the calculations), except for those coefficients related to changes in the puncture area, discharge coefficient, and elevation of the puncture; these are all nearly equal to one.

The nominal values of the output for the liquid discharge part of the venting are: liquid mass discharged = 5.69×10^7 grams; discharge time = 82.4 sec; and average discharge rate of the liquid = 6.9×10^5. The sensitivity coefficients for these outputs are given in Table D.1, for both increases (+) and decreases (-) of the indicated input. A discussion of these coefficients follows.

Tank volume. Increasing the tank volume increases the percentage of the liquid below the puncture, and similarly for decreasing the tank volume. The sensitivity coefficients for discharge mass and time therefore depend on where the puncture is with respect to the liquid surface; this explains the nonzero values of the coefficients. The average flow rate changes little.

Tank height. Changes in tank height have the same kind of effects as changes in tank volume, for the same reason, except that the direction of the change of the output is reversed.

TABLE D.1. SENSITIVITY COEFFICIENTS FOR LIQUID OUTFLOW OF LNG AT -159.2°C

Input Parameter		Discharged Mass	Discharge Time	Average Flow Rate
Tank Volume	+	-0.36	-0.52	0.16
	-	0.42	0.66	-0.23
Tank Height	+	0.81	0.73	0.08
	-	-0.86	-0.75	-0.11
Puncture Area	+	0	-0.85	0.89
	-	0	0.93	-0.89
Discharge	+	0	-0.85	0.89
	-	0	0.93	-0.89
Initial Mass	+	1.48	1.72	-0.22
	-	-1.37	-1.48	0.12
Initial Temperature	+	≈ 0	-22.59	29.19
	-	≈ 0	65.69	-39.64
Atmospheric Pressure	+	0	0.20	-0.19
	-	0	-0.16	0.16
Atmospheric Temperature	+	0	0	0
	-	0	0	0

Puncture area and discharge coefficient. These inputs always occur in the combination A_pC_D; their individual effects are identical. Changes in them do not affect the total mass discharged. The average flow rate and discharge time, however, are almost related one-to-one (i.e., $S = \pm 1$) to the changes in Z_p or C_D. If the liquid did not change phase and the tank pressure remained constant, the coefficients would be exactly ± 1.

Initial mass. Since the quantity of liquid below the puncture is constant, changes in the total initial liquid mass have a slightly greater than one-to-one effect on both the mass discharged and discharge time.

Initial temperature. Changes in the initial temperature have a negligible effect on the total mass that is discharged, but have a great effect on the discharge time. A one percent change in temperature changes the initial tank pressure by nine percent and the initial pressure differential at the puncture by over fifty percent, so the large sensitivity coefficients are understandable.

Atmospheric pressure. Changing the atmospheric pressure changes the pressure differential from the tank to the outside, so the discharge rates and times are affected. If air ingestion had occurred, the sensitivity coefficients would have been larger. On the other hand, if the vacuum relief valve had been operable, the sensitivity to atmospheric pressure would have been very small.

Atmospheric temperature. Since air was not ingested, the temperature of the atmosphere had no effect.

It can be concluded that only the sensitivity of the results to the initial temperature might create a problem in practice. Even then, the sensitivity would be large only for volatile liquids carried in pressurized tanks or in tanks whose relief valve is stuck, so that super- or sub-atmospheric tank pressures are possible.

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